Assessing the impact of land use change on hydrology and sediment yield in the Xiangxi Catchment (China) using SWAT

Dissertation

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One axiom associated with rivers is that what initially appears complex is even more so upon further investigation.

D.L. Rosgen, 1994

Summary

The Three Gorges Region is located in Hubei Province and Chongqing Municipality in Central China. It is heavily influenced by the construction of the Three Gorges Dam on Yangtze River, which was completed in 2009. The dam was constructed for reasons of flood protection, hydropower production and navigation benefits. It exerts substantial influence on water resources in the affected sub-watersheds of Yangtze River.

In the Three Gorges Region, the construction of the Three Gorges Dam induced a large-scale land use change. This can mostly be attributed to the inundation of agricultural areas, villages and towns, which necessitated the resettlement of more than 1 million people and the relocation of agriculturally used areas from the valley bottoms to steep, formerly forested slopes. The clearance of forest on steep slopes and their use for agricultural production is expected to strongly increase the risk of erosion and diffuse sediment inputs to surface waters. Soil erosion results in the removal of nutrient-rich topsoil, which leads to an irreversible degradation of soils and to undesired off-site effects in surface waters. The sediment reduces the life span of the Three Gorges Reservoir due to siltation and carries large amounts of nutrients to the water bodies. At the same time, flow velocities are reduced and the residence time of water is prolonged in the reservoir. In combination, the increasing sediment and nutrient inputs and the altered flow regime are expected to exacerbate the risk of eutrophication and thereby hamper the usability of water resources. Especially in the backwater areas of Yangtze River tributaries, an increasing occurrence of algae blooms has been observed in recent years.

The current situation in the Three Gorges Region indicates a strong need for sustainable water resources management. This dissertation aimed at identifying a suitable tool for assessing the impact of land use change in the Three Gorges Region on water quantity and quality to support the development of integrated watershed management plans. Therefore, the eco-hydrological model SWAT (Soil and Water Assessment Tool) was applied to the Xiangxi Catchment in Hubei Province. The Xiangxi Catchment comprises an area of 3200 km^2 as is considered to be representative of the eastern part of the Three Gorges Region. Land use in the watershed is dominated by forest. Agriculturally used areas are restricted to relatively small areas, which are characterized by severe soil erosion.

SWAT was used in this dissertation to simulate water balance, streamflow and sediment yield under past, current and possible future land use conditions. Also, the most important sources of model error were identified in this study. Results indicate that the model performs very well with regard to streamflow and water balance, whereas the prediction of sediment yield is more problematic. SWAT output was analyzed at different spatial levels ranging from the entire watershed to individual Hydrologic Response Units. Generally, there is considerable uncertainty associated with the SWAT predictions in the Xiangxi Catchment, because of a low amount of data available for model parameterization, calibration and validation. Nevertheless results of the basic model calibration were considered a sufficient basis for the simulation of land use scenarios. The forested area in the Xiangxi Catchment has increased in the recent past which led to a decrease of fast flow components and sediment yield. Scenario simulations demonstrate that a further increase in forest would result in a continuation of the trends observed in the past, whereas an increase of agriculturally used areas would induce a strong increase in sediment yields. The scenario simulations indicate a high potential for conflicts between environmental protection and agricultural production, which is aggravated by conservation efforts of the Chinese government, e.g. the Sloping Land Conversion Program (SLCP). Through compensation and subsidy payments, SLCP encouraged farmers to convert sloping cropland to forest or grassland. While this is an effective means of reducing soil erosion on the afforested areas, it increases the pressure on the remaining cropland.

The results of this dissertation suggest that in the future the application of selected Best Management Practices may be more effective for realizing sustainable watershed management plans than continuing to reallocate land use types within the Xiangxi Catchment. SWAT has already been used successfully for assessing the effects of Best Management Practices on water resources in a number of studies. However, the data currently available for the Xiangxi Catchment does not allow for a sufficiently detailed parameterization and calibration of land use and management.

Future studies in the Xiangxi Catchment should focus on improving the data base by obtaining additional relevant input data. This can help to reduce the uncertainty in model results and facilitate the simulation of Best Management Practices. By testing the applicability of SWAT to the Xiangxi Catchment and identifying the main sources of uncertainty, this dissertation laid the groundwork for further research in the Three Gorges Region, which can help to preserve natural resources in this unique and sensitive ecosystem.

Kurzfassung

Die Drei-Schluchten-Region befindet sich in den Provinzen Hubei und Chongqing in Zentralchina. Sie ist sehr stark durch den Bau des Drei-Schluchten-Staudamms am Yangtze beeinflusst, der im Jahr 2009 abgeschlossen wurde. Die Hauptgründe für den Bau des Staudamms waren Hochwasserschutz, Energiegewinnung und die Verbesserung der Schiffbarkeit des Yangtze. Der Staudamm und der damit einhergehende Aufstau eines großen Stausees beeinflussen die Wasserressourcen der betroffenen Teileinzugsgebiete des Yangtze erheblich.

In der Drei-Schluchten-Region kam es zu einem großflächigen Landnutzungswandel, der sich auf die Überflutung von Ackerflächen, Dörfern und Städten zurückführen lässt. Über eine Million Menschen mussten umgesiedelt und Ackerflächen von den flachen, fruchtbaren Talböden an die steilen, vormals bewaldeten Hänge verlagert werden. Die Umwandlung von Wald zu Ackerland auf steilen Hängen kann zu einer Erhöhung des Erosionsrisikos und zu steigenden Sedimenteinträgen in Oberflächengewässer führen. Der fruchtbare Oberboden wird von den Flächen abgetragen, was zu einer irreversiblen Degradierung der Böden und zu negativen Effekten in den Oberflächengewässern führt. Das Sediment wird im Drei-Schluchten-Stausee abgelagert und verringert dessen Stauvolumen. Außerdem führt es erhebliche Mengen an Nährstoffen mit sich. Gleichzeitig kam es durch den Aufstau zu einer Verringerung der Fließgeschwindigkeiten und zu einer Verlängerung der Verweilzeiten des Wassers. Die Kombination dieser Veränderungen führt zu einer Erhöhung des Eutrophierungsrisikos im Stausee. Besonders in den Aufstaubereichen der Nebenflüsse des Yangtze wurden in den vergangenen Jahren bereits vermehrt Algenblüten beobachtet.

Die derzeitige Situation in der Drei-Schluchten-Region erfordert ein nachhaltiges Management der Wasserressourcen. Die vorliegende Dissertation beschäftigt sich mit der Identifikation eines geeigneten Werkzeugs zur Erfassung der Auswirkungen des Landnutzungswandels in der Drei-Schluchten-Region auf die Wassermenge und -qualität, um ein integriertes Wasserressourcenmanagement zu unterstützen. Das öko-hydrologische Modell SWAT (Soil and Water Assessment Tool) wurde im 3200 km^2 großen Xiangxi-Einzugsgebiet in der Provinz Hubei angewandt. Das Untersuchungsgebiet ist durch einen hohen Waldanteil gekennzeichnet und wird als repräsentativ for die östliche Drei-Schluchten-Region angesehen. Ackerbaulich genutzte Flächen nehmen nur kleine Teile des Gebiets ein, zeichnen sich jedoch durch sehr hohe Erosionsraten aus.

Das Modell SWAT wurde genutzt, um den Abfluss, die Wasserbilanz und den Sedimenttransport unter ehemaliger, heutiger und möglicher zukünftiger Landnutzung abzubilden. Zudem wurden die wichtigsten Ursachen für Unsicherheiten in den Modellergebnissen identifiziert. Die Ergebnisse zeigen, dass SWAT in der Lage ist, gute Simulationsergebnisse für den Wasserhaushalt und den Abfluss im Xiangxi-Einzugsgebiet zu liefern. Die Abbildung des Sedimenttransports stellte sich als problematischer heraus. Die Modellergebnisse wurden auf verschiedenen räumlichen Skalen vom gesamten Einzugsgebiet bis hin zu einzelnen Hydrotopen analysiert. Generell sind die Simulationsergebnisse mit hohen Unsicherheiten verknüpft, was sich auf die unzulängliche Verfügbarkeit von Messdaten zur Parametrisierung, Kalibrierung und Validierung des Modells zurückführen lässt. Dennoch wird das kalibrierte Ausgangsmodell als geeignete Grundlage für die Simulation von Landnutzungsszenarien angesehen.

Die bewaldete Fläche im Xiangxi-Einzugsgebiet hat in den vergangenen Jahrzehnten leicht zugenommen, was zu einer Abnahme des Oberflächenabflusses und des Sedimenttransports geführt hat. Simulationsergebnisse zeigen, dass eine weitere Zunahme der Waldflächen diesen Trend fortsetzen würde, während eine Zunahme der Ackerflächen zu einer starken Erhöhung des Sedimenttransports führen würde. Die Modellergebnisse deuten auf einen hohes Konfliktpotenzial zwischen den Interessen des Ressourcenschutzes und der Landwirtschaft hin. Zusätzliche Einflussfaktoren in der Drei-Schluchten-Region sind Programme der chinesischen Regierung zum Schutz der natürlichen Ressourcen, wie beispielsweise das Sloping Land Conversion Program (SLCP). Dieses versuchte, durch Subventionszahlungen einen Anreiz zur Umwandlung von Ackerland in Wald oder Grünland zu schaffen. Dies hat sich als effektive Erosionsschutzmaßnahme auf den umgewandelten Flächen herausgestellt, jedoch gleichzeitig den Druck auf die verbleibenden Ackerflächen erhöht.

Die Ergebnisse dieser Dissertation deuten an, dass die Etablierung von konservierenden Maßnahmen in der Landwirtschaft in Zukunft ein effektiveres Werkzeug für den Ressourcenschutz sein kann als eine Fortsetzung der Umverteilung von Landnutzungsarten im Xiangxi-Einzugsgebiet. SWAT wurde bereits in mehreren Studien erfolgreich für die Abschätzung der Wirksamkeit verschiedender Maßnahmen zum Bodenschutz eingesetzt. Derzeit erlaubt die eingeschränkte Datenbasis eine entsprechende Nutzung des Modells im Xiangxi-Einzugsgebiet nur bedingt.

Zukünftige Studien im Xiangxi-Einzusgebiet sollten sich auf eine Verdichtung der Datenbasis konzentrieren. Dies kann dazu beitragen, die Unsicherheiten in den Modellergebnissen zu reduzieren und die modellgestützte Simulation von Boden- und Gewässerschutzmaßnahmen zu ermöglichen. Durch das Überprüfen der Modellanwendbar-keit im Xiangxi-Einzugsgebiet und die Identifikation der wichtigsten Ursachen für Modellunsicherheiten hat diese Dissertation die Grundlage für weitere Forschung in der Drei-Schluchten-Region geschaffen und einen Beitrag zum Schutz natürlicher Ressourcen in diesem einzigartigen und sensiblen Ökosystem geleistet.

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Chapter 1

Introduction

1.1 Motivation

Land use is rated as one of the most important factors influencing water quantity and quality in watersheds. Not only are hydrological processes such as evapotranspiration, infiltration, surface runoff and groundwater flow altered substantially by land use changes, but also soil erosion and the transport of sediment to water bodies (Bultot et al. 1990; Fohrer et al. 2001; Lin et al. 2007; Sahin and Hall 1996; Tong and Chen 2002). DeFries and Eshleman (2004) state that "land use is a major issue for this century" and suggest that understanding the impacts of land use change on hydrologic processes is a central research need for the future. The evaluation of the impacts of land use change on water quantity and quality is fundamental to the development of sustainable land use alternatives (Lenhart et al. 2003; Lin et al. 2007) and is an integral component of river basin and water resources management (Eckhardt et al. 2003; Huisman et al. 2004).

The deterioration of water resources constrains their function as a habitat for plants and animals and their usability for human consumption, fisheries and recreation (Mainstone et al. 2008). While point sources are easy to locate and often contribute relatively constant inputs over long periods of time, diffuse sources are more difficult to assess due to their extensive spatial occurrence and their temporal variability depending on a number of factors including climate and land use (Carpenter et al. 1998). Agriculture is considered to be the dominant contributor to diffuse inputs of sediment and phosphorus to surface waters (Gächter et al. 2004; Mainstone et al. 2008).

Erosion and non-point source pollution of rivers with agricultural sediments and nutrients are major environmental problems in the Three Gorges Region in China (Heggelund 2006; Shen et al. 2010a; Tian et al. 2010). The construction of the Three Gorges Dam on the Yangtze River has induced a large scale land use change in the affected watersheds. The most important driver of this land use change is the inundation of agricultural areas, towns and villages due to the reservoir impoundment (Seeber et al. 2010), which forced people to resettle and relocate their cropland from the fertile valley bottoms to steeply sloping uphill areas with shallow soils characterized by a poor structure and low organic matter contents (Shi et al. 2004). This is expected to influence not only the water balance in the affected watersheds, but also the diffuse inputs of sediment and nutrients to rivers caused by an increase in erosion (Lu and Higgitt 2000; Meng et al. 2001; Schönbrodt et al. 2010). High soil erosion rates and sediment inputs can lead to sedimentation in the Three Gorges Reservoir and thus impact its operation and life span (Higgitt and Lu 2001; Shi et al. 2004). Also, a higher risk of reservoir eutrophication is expected because of increasing inputs of nutrients, especially phosphorus, adsorbed to sediment and reduced flow velocities and prolonged residence times of water in the reservoir (Dai et al. 2010; Zeng et al. 2006). Additionally, sediment deposited in the reservoir might desorb large amounts of phosphorus (Wang et al. 2009) and thereby further increase the eutrophication risk. Since the impoundment of the Three Gorges Reservoir started, an increasing occurrence of algae blooms has been observed, especially in the backwater areas of Yangtze River tributaries (Li et al. 2008; Ye et al. 2007; Xu et al. 2010b, 2011b; Zeng et al. 2006; Zhang et al. 2010a; Zhong et al. 2005).

Luo et al. (2010) stress the importance of a profound knowledge of diffuse inputs as an prerequisite for sustainable water resources management in the Three Gorges Region. It is crucial to assess and quantify the impact of changes in land use and management on the water quantity and quality of the watersheds affected by the impoundment of the Three Gorges Reservoir and to develop sustainable land use scenarios in order to mitigate the negative effects of the Three Gorges Project. The possibilities to conduct field experiments are limited, because field work is time-consuming and costly. Therefore, hydrological and water quality models are valuable tools and often the only feasible way of evaluating land use change and management scenarios (Fohrer et al. 2001; Arabi et al. 2006; Behera and Panda 2006; Ahl et al. 2008). The use of models not only facilitates the quantification of the impacts of land use and management on water quantity and quality, but also the identification of Critical Source Areas within a watershed where the implementation of Best Management Practices to improve the status of water resources needs to focus on (Chaubey et al. 2005). However, Xu et al. (2011a) point out that currently there is no suitable analytical tool for quantifying the environmental effects of the land use change induced by the resettlement of the local population and the relocation of agricultural areas in the Three Gorges Region. An important step towards filling this gap in knowledge is the identification of adequate models and highlighting further research needs. Therefore, this dissertation aims at testing the applicability of the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998), a widely used watershed model, for simulating water balance, streamflow and sediment yields as a function of land use change in a watershed in the Three Gorges Region and identifying the capabilities as well as the limitations of this methodology.

1.2 The Three Gorges Project and its impacts on water resources

1.2.1 Yangtze River and the Three Gorges Dam

The 6,300 km long Yangtze River (Figure 1.1) is the longest river in China and the third longest in the world. With a size of 1,800,000 km^2, its catchment comprises 19% of the total land area of China (Liu and Zuo 1987). The source of the Yangtze is located on the Qinghai-Tibet Plateau in western China on elevations of more than 5,500 m.a.s.l. (King et al. 2002). The upper reaches of Yangtze River extend over a distance of more than 4,300 km from the source to the City of Yichang. The 950 km long river section between Yichang and Hukou at the outlet of Poyang Lake is referred to as the middle reaches of Yangtze River. At Hukou, the lower reaches of Yangtze River begin, which extend over a distance of 930 km. The Yangtze River flows through 10 Chinese provinces with a population of about 400 billion people before discharging into the East China Sea near the city of Shanghai (Subklew et al. 2012). On average, the river discharges 960 billion m^3 of water per year (King et al. 2002), which is equivalent to 37% of China's annual water yield. The mean annual discharge amounts to 30,166 m^3 s^{-1}. Ranging from 3,000 m^3 s^{-1} in January up to 60,000 m^3 s^{-1} in summer, Yangtze River discharge is characterized by a large seasonal variability.

The Three Gorges Region is located in the lower part of the upper reaches of Yangtze River and comprises 19 counties between the Cities of Chongqing and Yichang (Bu et al. 2008). It covers a total area of 62,640 km^2 (Wang et al. 2010). The Three Gorges Region was named after the three gorges Qutang Gorge, Wu Gorge and Xiling Gorge.

The Three Gorges Dam was constructed near the village of Sandouping, which is located approximately 40 km upstream of Yichang. The first proposition for building a large dam in the Three Gorges Region were made in 1919 already. However, plans were put on hold repeatedly until the then Prime Minister of China, Li Peng, managed to gain political support for the project in 1992 (Hartmann and Becker 2003). Dam construction started in 1993 and was completed in 2009 (Zhang et al. 2009).

Figure 1.1: Map of the Yangtze River (Source: Lenton and Muller 2009)

The Three Gorges Dam (Figure 1.2) is more than 2 km long and its crest reaches an elevation of 185 m.a.s.l. The maximum water level of 175 m.a.s.l. was reached for the first time in autumn 2009. At this water level, the reservoir is more than 600 km long and on average 1.1 km wide. With a total volume of 39.1 billion m^3, it has a flood retention capacity of 22.1 billion m^3 (Ming et al. 2009). In late winter and spring, before the monsoon season starts, the water level in the Three Gorges Reservoir is lowered to an elevation of 145 m.a.s.l. in order to increase the discharge in the middle and lower reaches of Yangtze River for navigation benefits and to ensure a sufficient storage volume for the retention of large amounts of runoff occurring during the rainy season in summer (Subklew et al. 2012).

The Three Gorges Project is one of the largest dam projects in the world (Tian et al. 2010). The main objectives of constructing the Three Gorges Dam were flood control, power generation and navigation benefits (Morgan et al. 2012). However, the project has been discussed controversially ever since the first plans for building a large dam on Yangtze River came up (Hartmann and Becker 2003; Morgan et al. 2012). Before construction of the dam started, a detailed feasibility study was conducted (CIPM 1988). However, the construction of infrastructure near the dam site already started before the impact assessment was completed, which raised serious concerns with regard to the role of environmental issues during the process of decision-making (Fearnside 1988).

The Three Gorges Dam is expected to have large-scale and partly still unforeseeable consequences on ecology and water resources both in the Three Gorges Region and in the middle and lower reaches of Yangtze River including Poyang Lake and the Yangtze River Delta. Also, the validity of the main reasons for constructing the Three Gorges Dam is doubted by some authors. The sediment loads entering the middle and lower reaches from the upper reaches of Yangtze River have been reduced considerably (Li et al. 2011). Various authors (Chen et al. 2009; Xu and Milliman 2009; Zhang et al. 2009) observed increasing channel erosion downstream of the Three Gorges Dam, which is expected to lead to river bank and levee failures and hamper flood control and navigation in the middle and lower reaches of Yangtze River and to strongly affect the development of the Yangtze River Delta. Nakayama and Shankman (2013) expect an increase in flood risk in the middle and lower reaches of Yangtze River during the early summer monsoon instead of the proposed decrease. This can be attributed to a stronger channel incision resulting from the reduced sediment loads, which causes the river stage to be below the level required for floodwater to access flood retention areas (Nakayama and Shankman 2013). Especially in the densely populated Poyang Lake Region, the risk of severe floods has not been eliminated, but rather increased by constructing the Three Gorges Dam (Shankman et al. 2009), because the interaction of Yangtze River with Poyang Lake was substantially altered (Guo et al. 2012; Nakayama and Shankman 2013).

Figure 1.2: The Three Gorges Dam (left) and the reservoir (right) in September 2005

The Three Gorges Region is one of the most ecologically sensitive areas in China (Tian et al. 2010). It is strongly influenced by the Three Gorges Project (Shen et al. 2010a). A detailed introduction to the impacts of dam construction and reservoir impoundment on the water resources in the Three Gorges Region particularly with regard to sediment inputs to rivers is given in the following chapter.

1.2.2 Impacts of the Three Gorges Project

The Three Gorges Region is heavily influenced by soil erosion and non-point source pollution of surface waters with sediments and nutrients (Lu and Higgitt 2001; Shen et al. 2010a, 2010b; Tian et al. 2010). Before the construction of the dam, the annual soil loss in the Three Gorges Region and the annual sediment delivery to the Yangtze River were estimated at 157 million and 41 million tons, respectively (Shi et al. 1992). An estimated area of 33,000 km^2 in the region is affected by moderate or severe soil erosion (Ng et al. 2008), which is mostly attributed to the use of steep slopes for agricultural production (Lu and Higgitt 2001). The risk of soil erosion is closely related to land use (Long et al. 2006). Shi et al. (2004) estimated soil erosion in the Wangjiaqiao Catchment in Zigui County using the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997) and found erosion from agriculturally used areas on steeper slopes to be twice as high as erosion from flat or gently sloping areas. Because of the mountainous terrain, poor soils, a population exceeding the land carrying capacity and a lack of income alternatives, people in the Three Gorges Region are forced to adopt environmentally unfriendly and unsustainable cultivation practices (Jim and Yang 2006). Since dam construction started, land use in the Three Gorges Region has been influenced by a number of factors increasing the pressure on the land area. This led to an intensification of land use, which is presumed to increase surface runoff, erosion and sediment inputs to surface waters.

According to official numbers, more than 1 million people had to be resettled because of the impoundment of the Three Gorges Reservoir (Tan and Yao 2006; Xu et al. 2011a). Many of them were resettled within their original counties and moved upslope to steep, formerly forested areas, abandoning prime agricultural land in the valleys and leaving it to inundation. Zhang et al. (2009) state that approximately 240 km^2 of agricultural land were flooded by the Three Gorges Reservoir, while Lu and Higgitt (2001) estimate the submerged agricultural land at 316 km^2. The soils on steep slopes are mostly of poor structure and characterized by a low organic matter content (Shi et al. 2004) and are much less productive than the soils in the river valleys. Shi et al. (1992) estimated a need of five times the previous agricultural area in order to produce the same amount of harvest on sloping cropland (Lu and Higgitt 2001). Also, the Three Gorges Project has boosted the regional economy considerably and the region has experienced a strong growth in population, both increasing the demand for agricultural products on the one hand and built-up area on the other hand (Zhang et al. 2009).

As a result of erosion and sediment transport, the nutrient-rich topsoil is removed from the agricultural areas, leading to an irreversible degradation of soils and to undesired off-site effects in water bodies. The sediment reduces the life span of the Three Gorges Reservoir due to siltation (Higgitt and Lu 1996, 2001; Wang et al. 2010). Also, it carries large amounts of nutrients to the water bodies (Ouyang et al. 2010). Especially phosphorus, which has been shown to be the limiting nutrient in most inland surface waters (Haygarth et al. 2005; Mainstone and Parr 2002) including Yangtze River and its tributaries (Liu et al. 2003), tends to adsorb to soil particles (Scheffer et al. 1992). This causes a close correlation of the transport of sediment and phosphorus in a watershed (Heathwaite and Johnes 1996). Ongley et al. (2010) assume that 85% of the phosphorus load in Chinese rivers comes from diffuse, agricultural sources. The amount of mineral fertilizer used in China in 2004 is estimated to be four times larger than 1979 (Chen et al. 2008). According to Zhao et al. (2008), the amount of phosphorus applied in Chinese agriculture is twice as high as the global average, but the efficiency of use only amounts to 30 to 40%. Chen et al. (2008) estimate the average phosphorus input and output in Chinese agriculture at 28.9 and 14.2 kg ha^{-1} a^{-1}, respectively, which results in a surplus of more than 50%.

Especially in the backwater areas of the Yangtze River tributaries, algae blooms have been observed more frequently since the construction of the Three Gorges Dam (Zhong et al. 2005; Zeng et al. 2006; Ye et al. 2007; Li et al. 2008; Dai et al. 2010; Zhang et al. 2010a; Xu et al. 2011b). The aggravation of the water quality problems in the Three Gorges Region is not only attributed to the large-scale land use change, but also to the modified flow regime of Yangtze River. The flow velocity in the reservoir is reported to be at least five times lower than before the impoundment, which prolongs the residence time of the water (Tullos 2009; Dai et al. 2010; Xu et al. 2011b). The trophic status of standing and slowly flowing waters reacts sensitively even to marginal changes in phosphorus concentrations (Johnes and Hodgkinson 1998). Also, sediment deposited in the reservoir can potentially desorb considerable amounts of phosphorus (Wang et al. 2009). Sediment-bound phosphorus can still pose a threat to water quality long after inputs from the watershed have been minimized (Lijklema et al. 1993; Abrams and Jarrell 1995). In combination, these factors are assumed to increase the risk of eutrophication in the Three Gorges Reservoir substantially (Dai et al. 2010).

The situation in the Three Gorges Region is further complicated by the Sloping Land Conversion Program (SLCP), which was launched in 1999 as a consequence of the devastating Yangtze River floods in 1998 (Bennett 2008). Due to the high erosion rates, the Three Gorges Region is one of the main target areas of SLCP. Through compensation and subsidy payments, farmers were encouraged to convert agricultural land on slopes >25° to forest or grassland (Xu et al. 2006; McVicar et al. 2007; Wang et al. 2007; Ouyang et al. 2008). Depending on whether cropland is converted to grassland or to forest, farmers participating in the program receive payments for two to eight years, but their livelihood is not improved considerably (Long et al. 2006). It is assumed that many farmers will be forced to convert the new grasslands or forests back to cropland once the subsidy payments have stopped. Jim and Yang (2006) and Long et al. (2006) criticize the lack of efforts to create long-term, non-agricultural sources of income, optimize the local agricultural structure and improve cultivation techniques. While SLCP has been shown to be an effective means of reducing soil erosion in the afforested areas, it also decreased the land area available for agriculture and put further pressure on the remaining areas of cropland (Jim and Yang 2006).

1.3 Materials and Methods

1.3.1 The Yangtze Project

The Yangtze Project is a Sino-German research collaboration that has been funded by the German Federal Ministry of Education and Research (BMBF) since 2008. The overall coordination was assigned to the Forschungszentrum Jülich GmbH. The aim of the Yangtze Project is to investigate the environmental impacts of the Three Gorges Dam construction and the reservoir impoundment (Subklew et al. 2010). Research in the framework of the Yangtze Project was divided into four general topics of which so far only the latter two are funded by the BMBF:

1. atmosphere,
2. vegetation and biodiversity,
3. interactions of water, sediment and contaminants,
4. land use change, soil erosion, mass movements and diffuse inputs.

The results of this dissertation were generated in the context of the topic land use change, soil erosion, mass movements and diffuse inputs (Yangtze-GEO). The general objective of Yangtze-GEO is to develop and test an integrated methodology for the analysis of land use change and vulnerability and the risk assessment of mass movements, soil erosion and diffuse inputs to rivers. This objective was pursued during a first phase from 2008 through 2011 within five sub-projects at the universities of Tübingen, Erlangen, Giessen, Potsdam and Kiel (Figure 1.3). In July 2012, a second phase started with minor alterations to the project partners involved.

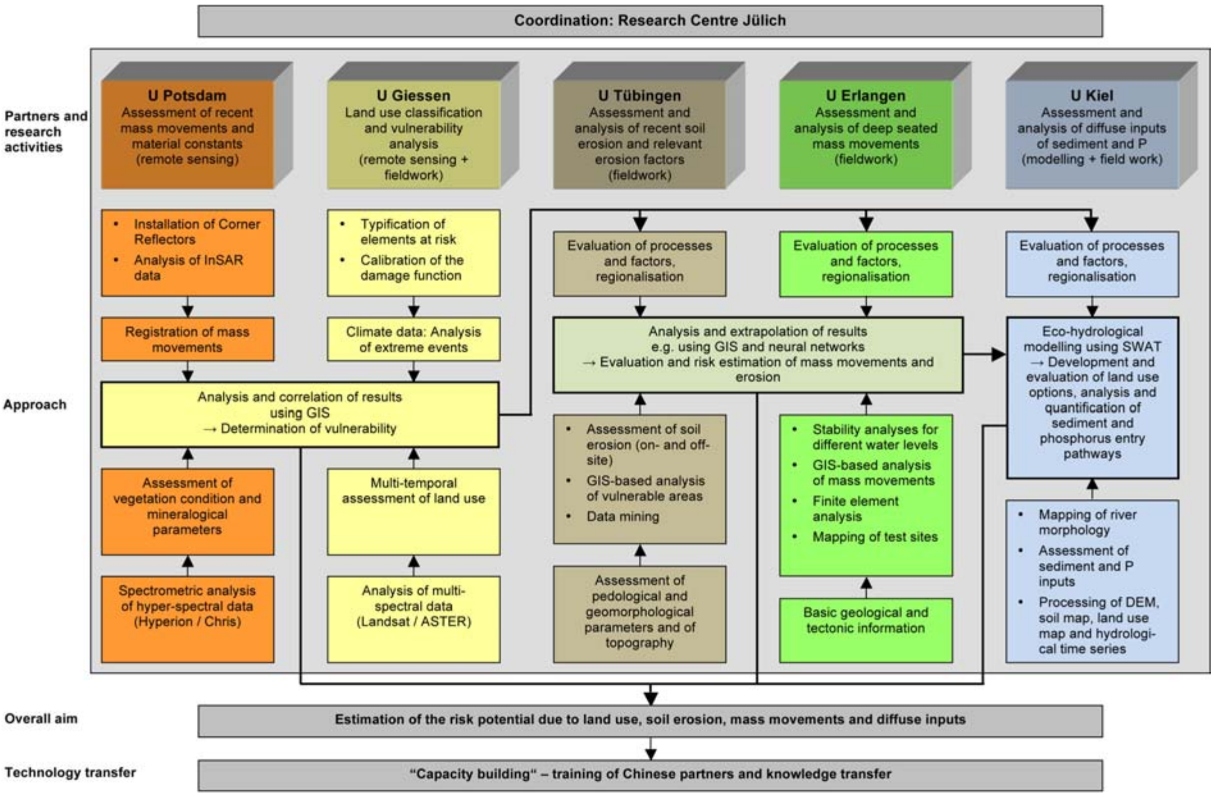

Figure 1.3: Project partners involved in the first phase of the Yangtze-GEO project, their central methodology and the main cross-linkages of sub-projects (after Scholten and Schönbrodt-Stitt 2012)

During the first phase, all research within the Yangtze-GEO project focused on the Xiangxi Catchment in Hubei Province. Various cross-linkages between different sub-projects facilitated a detailed assessment of the interactions of land use dynamics with soil erosion, mass movements and sediment inputs to rivers. Results of all sub-projects were made available to all project partners, so output from one sub-project could be used as input for another one. The final report for the first phase of Yangtze-GEO including a detailed description of the most important activities and results of each sub-project was published by Scholten and Schönbrodt-Stitt (2012).

1.3.2 The Xiangxi Catchment and available data

The Xiangxi Catchment extends from 30°57'23''N to 31°40'7''N and from 110°17'34''E to 111°7'40''E (Figure 1.4) and covers most of Xingshan County as well as parts of Zigui and Shennongjia Counties. The watershed comprises a total area of 3,200 km^2.

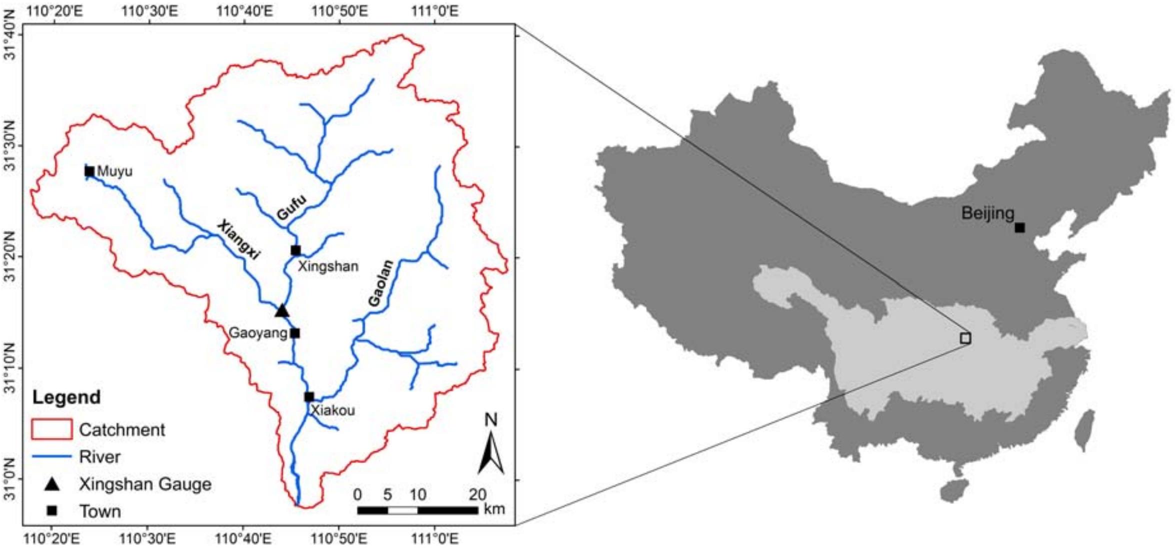

Figure 1.4: Location of the Xiangxi Catchment in China, the watershed boundary and river network and the location of towns and Xingshan Gauge

The Digital Elevation Model (DEM) with a resolution of 90 x 90 m used in this study was downloaded from the SRTM database (Jarvis et al. 2008). The Xiangxi Catchment is characterized by very large differences in elevation (Figure 1.5). With up to 3,078 m, the highest elevations can be found near the source of the Xiangxi in the Shennongjia Mountains. At the outlet of the watershed, where the Xiangxi discharges into Yangtze River, elevations reach down to values as low as 62 m. With a mean gradient of 24° and a maximum gradient of 76° slopes in the watershed are very steep. Figure 1.6 visualizes the mountainous topography and the steep slopes prevalent in the Xiangxi Catchment.

The Xiangxi River is 94 km long and has two large tributaries, the Gufu and the Gaolan (Figure 1.4). The confluence of the Xiangxi with the Yangtze River is located approximately 40 km upstream of the Three Gorges Dam. The largest towns in the Xiangxi Catchment are Xiakou, Gaoyang, Muyu and the county seat Xingshan. Climate data is available for three stations, of which only one (Xingshan) is located within the watershed, whereas the remaining two, Shennongjia and Zigui, are located 13 and 6 km outside the watershed boundaries, respectively. Streamflow is measured at Xingshan Gauge in the centre of the watershed near the confluence of Xiangxi and Gufu Rivers. Until 2002, the gauge was located a few kilometers further downstream, but it had to be relocated because of the impoundment of Three Gorges Reservoir, which flooded the old gauge.

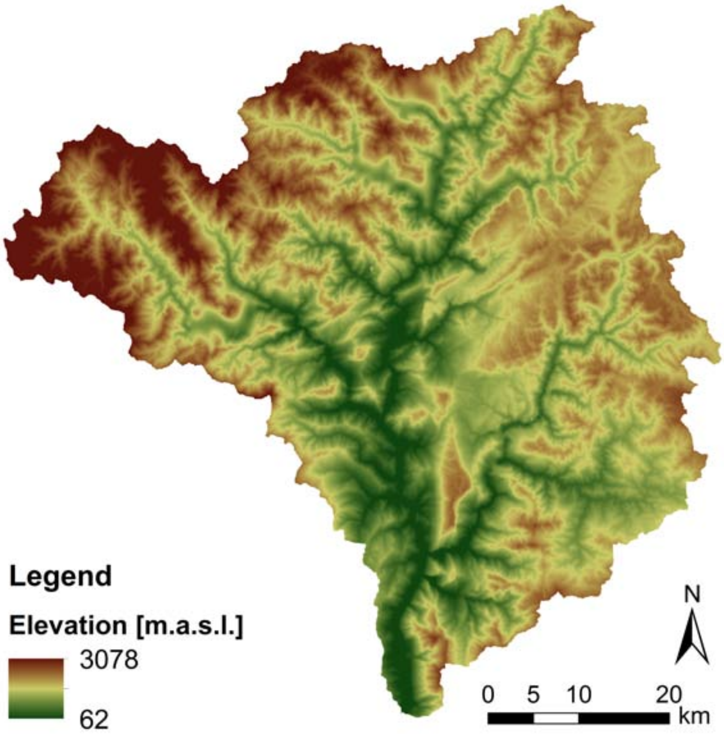

Figure 1.5: Digital elevation model of the Xiangxi Catchment

Figure 1.6: Mountainous topography of the Xiangxi Catchment (left) and steep slopes along the river (right)

Mean annual temperature and precipitation for the standard reference period (1961-1990) at the climate station Xingshan are 16.9°C and 1000 mm, respectively. The climate in the Xiangxi Catchment is strongly influenced by the subtropical summer monsoon, which entails a distinct seasonality of precipitation with very high amounts in summer and much lower amounts in winter. Temperature and precipitation are additionally influenced by the mountainous topography of the watershed and vary considerably with altitude (He et al. 2003).

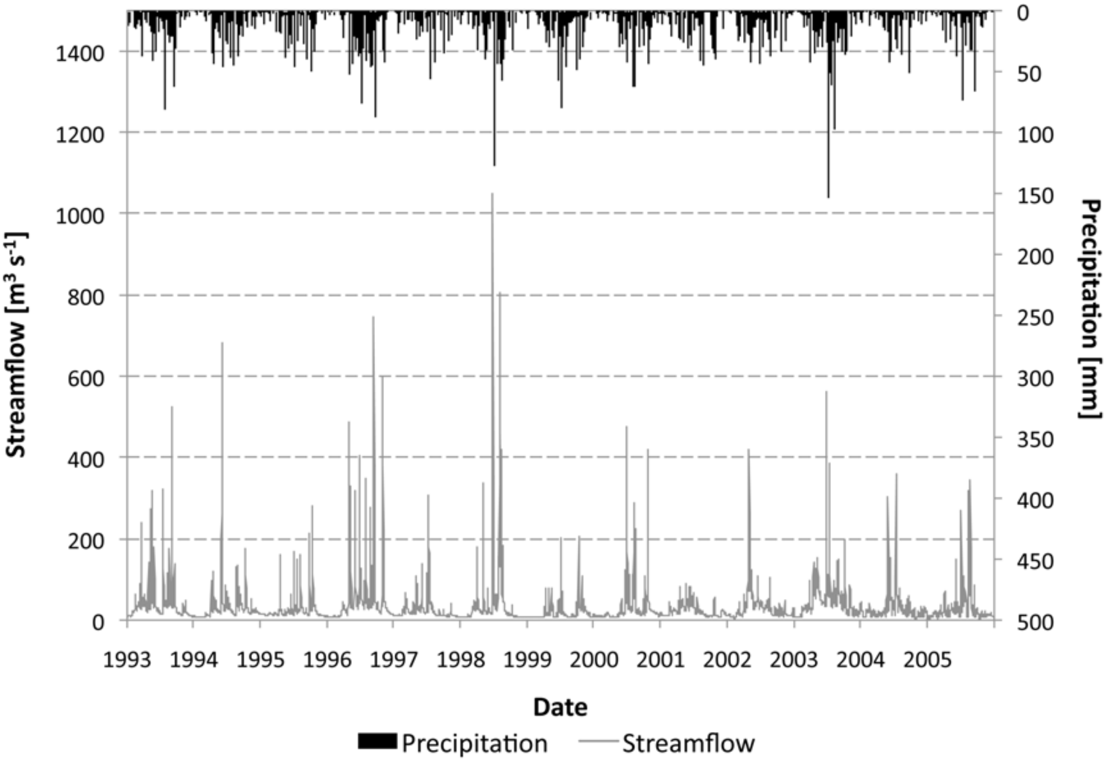

Figure 1.7: Streamflow at Xingshan Gauge and precipitation at Xingshan climate station from 1993 to 2005

Observed daily streamflow data for Xingshan Gauge in the centre of the watershed is available from 1970 through 2005 with data for the years 1975 and 1987 missing. During this period of time, mean annual streamflow amounted to 36.75 m^3 s^{-1}. In accordance with the seasonal variability of the climate, streamflow is very low in winter and flood events mainly occur in summer (Figure 1.7). In 1999 and 2004, two dams on Gufu River were put into operation, which changed the dynamics of streamflow at Xingshan Gauge considerably. Since then, streamflow peaks have been decreased, whereas there has been a stronger dynamic in the base flow during winter (Figure 1.7). Observed sediment loads are available at a daily time step from 1970 through 1986 with data for the year 1975 missing.

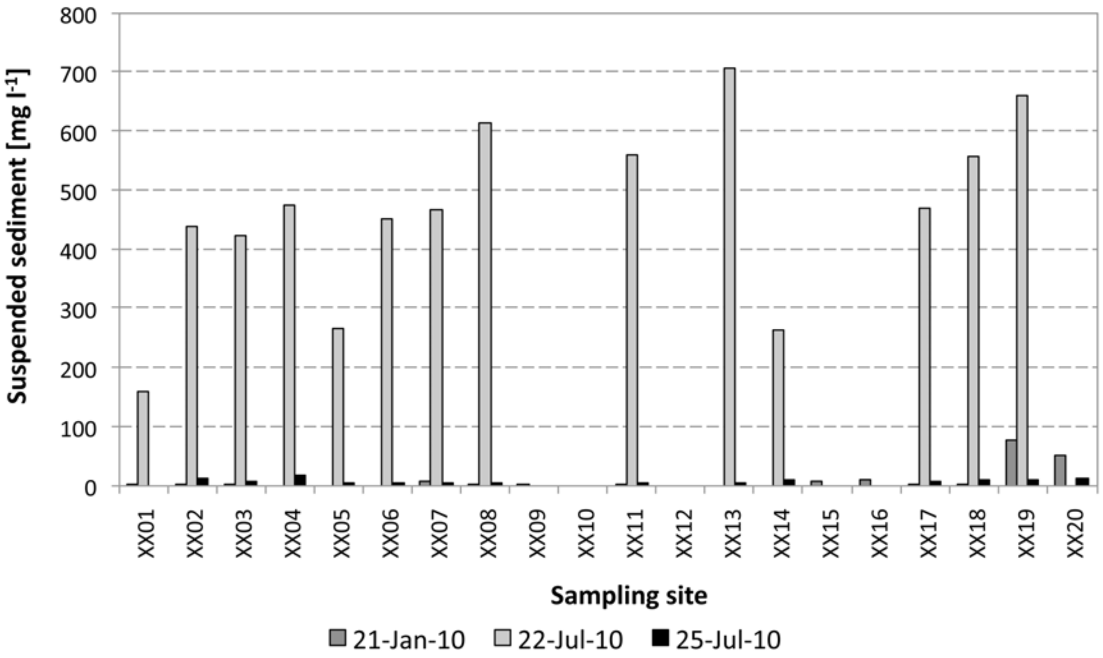

Figure 1.8: Suspended sediment concentrations at 20 sampling sites in Xiangxi River in January and July 2010

Figure 1.9: The middle reaches of Xiangxi River on January 21 (left), July 22 (middle) and July 25 (right), 2010

Li et al. (2008) found a strong dependence of sediment and nutrient transport in Xiangxi River on streamflow, which suggests that non-point sources are the main contributors to sediment and nutrient inputs in this watershed. This was confirmed by own observations in January and July 2010. In January 2010, water samples taken at various sampling sites along

Xiangxi River were characterized by very low sediment concentrations. On July 22 2010, samples were taken during a flood event. The sediment concentration in those samples was orders of magnitude higher than in the samples taken in January. When sampling was repeated on July 25 2010, three days after the flood event, sediment concentrations were almost as low as in January (Figures 1.8 and 1.9).

Since the Three Gorges Dam was closed and the reservoir impoundment started in 2003, the Three Gorges Reservoir has expanded progressively into Xiangxi River, transforming its lower 30 km into a narrow bay called Xiangxi Bay (Figure 1.10). According to Guo et al. (2003), 9,700 ha of cropland, forest and residential areas were submerged in the Xiangxi Catchment. The watershed is thus heavily influenced by the construction of the Three Gorges Dam and the reservoir impoundment. An increasing occurrence of algae blooms in Xiangxi Bay has been observed in the past few years (Zeng et al. 2006; Ye et al. 2007; Dai et al. 2010; Wang et al. 2011a, 2011b; Xu et al. 2011b; Zhou et al. 2011).

Figure 1.10: Xiangxi Bay at Xiakou

The soil map available for the Xiangxi Catchment was digitized from analogue soil maps of the counties Shennongjia, Xingshan and Zigui on a scale of 1:160000 to 1:180000 (Schönbrodt-Stitt et al. 2012; Figure 1.11), which were mapped during the Second National Soil Survey in China. Eight major soil types occur within in the watershed, which are named in this dissertation according to the Genetic Soil Classification of China (Shi et al. 2010). Covering 38 and 41% of the area, respectively, the dominant soil types in the watershed are Limestone soils and Yellowbrown soils. In the Shennongjia Mountains in the northwestern part of the Xiangxi Catchment, Darkbrown soils and Brown soils are located on high elevations. However, occupying 4 and 7% of the total watershed they are much less common than the

Yellowbrown and Limestone soils. Purple soils cover 5% of the watershed and can be found mostly west of the lower reaches of Xiangxi River. Yellow soils occupy 4% and occur in the central, southern and southeastern part of the watershed (Schönbrodt-Stitt et al. 2012). The remaining soil types are of minor importance as they cover marginal fractions of the Xiangxi Catchment.

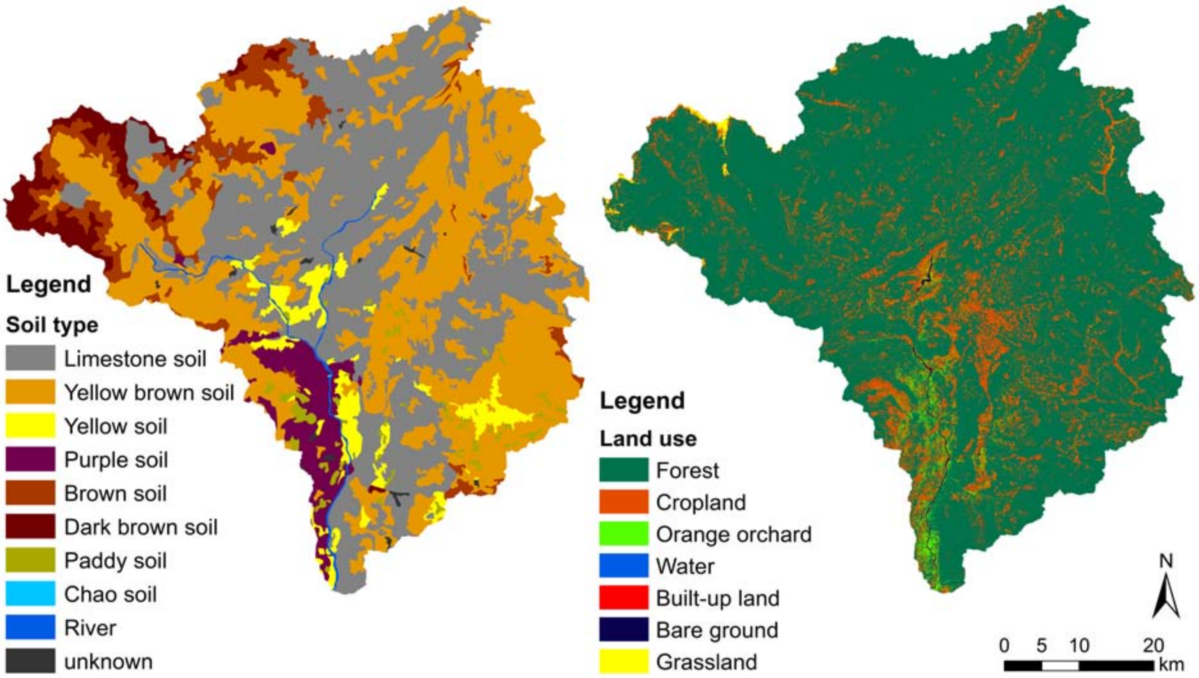

Figure 1.11: Soil map (after Schönbrodt-Stitt et al. 2012) and land use map for the year 1987 (after Seeber et al. 2012)

The development of land use and its driving forces was analyzed on the basis of three land use maps derived from Landsat TM images from the years 1987, 1999 and 2007 (Seeber et al. 2010, 2012). A total of seven land use classes were identified from the satellite images: forest, cropland, orange orchards, water, built-up land, bare ground and grassland. Forest is the dominating land use type in the Xiangxi Catchment, covering 83.7% of the watershed area in 1987 (Figure 1.11) and increasing to 87% in 2007. Deciduous forest is predominant in large parts of the watershed. On the highest elevation in the Shennongjia Mountains, forest is dominated by evergreen tree species and gradually transitions into grassland (Figure 1.12).

Figure 1.12: A mixture of evergreen forest and grassland in the Shennongjia Mountains (left) and deciduous forest near Muyu (right)

Agriculturally used areas are restricted to small areas. Larger proportions of cropland and orange orchards can be found in close proximity to rivers and roads, especially in the southern part of the watershed. On watershed average, cropland has decreased from 13.3 to 9.6% between 1987 and 2007; the percentage of orange orchards has increased from 1.7 to 2.3%. The increase in forest occurred mostly between 1987 and 1999 because of the abandonment of cropland in remote and inaccessible areas of the watershed. Between 1999 and 2007, forest increased marginally, but considerable areas of cropland were converted to orange orchards (Seeber et al. 2012). The remaining land use types water, built-up land, bare ground and grassland are of minor importance (Seeber et al. 2010).

Throughout the watershed, tea is planted as a cash crop on higher elevations (He et al. 2003), but could not be distinguished from forest on the satellite images (C. Seeber, personal communication, 2009). The Xiangxi Catchment is distinctive of the eastern part of the Three Gorges Region, which is generally dominated by forest with only small portions of cropland (Xu et al. 2011a). The most important crops are corn, rapeseed, sweet potatoes, cabbage, tobacco and rice. Figure 1.13 shows types of agricultural land use occurring in the Xiangxi Catchment.

Figure 1.13: Agricultural land use in the Xiangxi Catchment: Terraced cropland near Gaolan River after harvest in autumn (upper left), traditional farmhouse at Xiangxi River with tea and vegetable garden (upper right), corn and rice growing on terraces near Huangliangping (middle left), large-scale orange orchards at Gufu River (middle right), tea plantation near Muyu (lower left) and tobacco growing near Huangliangping (lower right)

1.3.3 The eco-hydrological model SWAT

For this study, the eco-hydrological model SWAT (Arnold et al. 1998) was chosen as a tool for assessing the impact of land use change on water quantity and quality in the Xiangxi Catchment. SWAT is a physically-based model, which was developed to predict the impact of land use and management practices on water, sediment and agricultural chemical yields in large watersheds. It is a continuous time model designed for simulating long periods of time (Arnold et al. 1998; Arnold and Fohrer 2005; Neitsch et al. 2011). According to the temporal resolution of the input data available and to the objectives of a study, SWAT can operate on a daily, monthly or yearly time step. Recent versions of the model also provide for simulations on a sub-daily time step if appropriate input data is available.

SWAT is a semi-distributed model. Based on the DEM, it divides the watershed into subbasins, which are further subdivided into hydrological response units (HRUs). These are lumped areas within a subbasin with a unique combination of slope, soil type and land use (Neitsch et al. 2011). While subbasins have a spatial reference within the watershed, HRUs are non-spatial proportions of a subbasin.

Simulation of the hydrologic cycle is separated into a land phase and a water phase. The simulation of the land phase is based on the water balance equation, which is calculated separately for each HRU:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \tag{1.1}$$

where SW_t is the final soil water content [mm], SW_0 is the initial soil water content on day i [mm], t is the time [days], R_{day} is the amount of precipitation on day i [mm], Q_{surf} is the amount of surface runoff on day i [mm], E_a is the amount of evapotranspiration on day i [mm], w_{seep} is the amount of water entering the vadose zone from the soil profile on day i [mm] and Q_{gw} is the amount of return flow on day i [mm].

Moisture and energy inputs needed to drive the hydrologic cycle are provided by the climatic variables precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity. These can be input from observed time series or simulated by a weather generator. Depending on the average daily temperature, precipitation will be classified as rain or snow.

Processes taken into account in an HRU include interception, evapotranspiration, infiltration, water movement in the soil profile and runoff. SWAT provides three options for estimating the potential evapotranspiration, the Hargreaves (Hargreaves et al. 1985), the Priestley-Taylor (Priestley and Taylor 1972) and the Penman-Monteith (Monteith 1965) methods. Water can be stored within an HRU in a deep and a shallow aquifer, in the soil profile and in the form of snow. Runoff can occur in an HRU as surface runoff, lateral flow and groundwater flow (return flow). Surface runoff is computed using either the SCS curve number method (SCS-CN; SCS 1972) or the Green & Ampt infiltration method (Green and Ampt 1911). Lateral flow depends on slope and the hydraulic conductivity and water content of the soil and is estimated using a kinematic storage model. Groundwater flow from the shallow aquifer contributes return flow to streams, whereas water entering the deep aquifer is assumed to be lost from the watershed. Runoff generated in the HRUs is summed up to calculate the amount of water reaching the main channel in each subbasin (Neitsch et al. 2011). The water phase of the hydrologic cycle describes the routing of runoff in the river channel, using either a variable storage coefficient method (Williams 1969) or the Muskingum routing method (Linsley et al. 1958).

Sediment yield is estimated for each HRU using the Modified Universal Soil Loss Equation (MUSLE; Williams 1975), which is a derivative of the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978). Sediment routing in the channel is controlled by two processes, degradation and deposition, with deposition occurring when the upland sediment load is larger than the transport capacity of the channel and degradation occurring when it is smaller. The transport capacity of a channel segment is calculated as a function of peak channel velocity (Arnold et al. 1995). In addition to sediment, the movement and transformation of several forms of nitrogen and phosphorus as well as the movement of pesticides in the watershed are also tracked in SWAT (Neitsch et al. 2011).

Central components of SWAT are the land cover/plant growth and the management modules. An extensive crop database stores plant parameters controlling potential growth, growth constraints, potential and actual transpiration and nutrient uptake of a large number of land use types and crops. Also, SWAT allows for detailed management schemes to be defined for each HRU, including timing of tillage, planting and harvesting, timing and amount of fertilizer and pesticides applications, irrigation and grazing. Crop rotations with different crops and management operations can be specified for any number of years. In SWAT2009, a land use update module was integrated for simulating land use change by changing the fractions of different HRUs occurring within a subbasin.

In accordance with the semi-distributed nature of SWAT, model parameters refer to one of three spatial levels, the watershed, the subbasin and the HRU level (Migliaccio and Chaubey 2008). Parameters at watershed level do not vary spatially within the watershed, e.g. Parameters related to snow fall and snow melt. Also, the methods used for computing evapotranspiration, surface runoff and channel routing have to be specified at the watershed level. Subbasins have a geographic location within the watershed and are spatially connected to each other (Neitsch et al. 2011). Parameters at subbasin level include the area and location of the subbasin, the physical characteristics of the channel (length, width, slope, hydraulic conductivity, roughness (Manning's n)) and parameters related to elevation bands. Elevation bands were introduced to SWAT by Fontaine et al. (2002) to represent differences in snowmelt-related processes with elevation. They provide the option to account for changes in temperature and precipitation with elevation, which are typically observed in mountainous watersheds. Parameters at HRU level describe the topographic characteristics of the HRU, maximum canopy storage, surface roughness (Manning's n), characteristics of potholes, general management parameters and scheduled management operations as well as soil and groundwater characteristics (Neitsch et al. 2011).

The graphical user interface ArcSWAT (Olivera et al. 2006) is a convenient tool for setting up SWAT, modifying input parameters and running the model. It writes all information required for a model run into the text files that are read by the SWAT executable. The SWAT source code is written in Fortran and can be downloaded from the website http://swat.tamu.edu/. This allows the user to modify subroutines within the model to improve the simulation of processes in a given watershed.

SWAT has been applied successfully in a number of physical settings and climate regions all over the world (Arnold and Fohrer 2005; Gassman et al. 2007). While during the first years after SWAT was released most studies focused on watersheds in North America and Europe, there is now an increasing number of model applications in developing and newly developed countries like China. According to Gassman et al. (2007) more than 40 studies have been performed using SWAT in China. It can be assumed that the number of Chinese studies has further increased in the past five years. Examples for recent SWAT applications in China are the studies of Zhang et al. (2003, 2010b, 2010c), Chen et al. (2005), Lai et al. (2006), Yu et al. (2007), Yang et al. (2007a, 2008, 2011), Guo et al. (2008), He et al. (2008), Wang et al. (2008), Ouyang et al. (2008, 2009, 2010), Huang et al. (2009b), Wu and Chen (2009), Ma et al. (2009, 2010), Xu et al. (2009), Shi et al. (2011), Xie and Cui (2011), Zheng et al. (2011), Luo et al.

(2012), Qiu et al. (2012), Song and Zhang (2012) and Tang et al. (2012). However, only a few studies focus on the Three Gorges Region (Hörmann et al. 2009; Shen et al. 2008, 2009, 2010a, 2012; Ye et al. 2009; Xu et al. 2010a; Gong et al. 2011).

1.4 Research questions and outline of thesis

This dissertation focuses on testing a methodology for the assessment of land use change impacts on water resources in the Xiangxi Catchment. The main objective was to lay the groundwork for applying SWAT in the Three Gorges Region in China to evaluate the effects of past, present and future changes in land use patterns on water quantity and quality with a limited amount of available data. The central research questions are:

1. Can analysis of observed data and uncalibrated model output help to acquire valuable information about key hydrological processes to promote SWAT model calibration in the Xiangxi Catchment?
2. Is SWAT capable of adequately simulating water balance, streamflow and sediment yield in the Xiangxi Catchment in the Three Gorges Region under past land use conditions?
3. Can the model be used to simulate land use scenarios for assessing the impacts of the large-scale land use change in the Three Gorges Region on water balance, streamflow and sediment yield?
4. How does the model perform at HRU level, i.e. the spatial scale that is most relevant for the identification of Critical Source Areas and the application of conservation measures?
5. What are the most important deficits of the SWAT model setup, parameterization and calibration for the Xiangxi Catchment?

Research questions 1 to 4 are each addressed in one of the following chapters. Research question 5 is aiming at a general topic that is very important in the field of hydrological modeling, especially in data-scarce regions, and that is therefore addressed - to a varying extent - in all of the following chapters.

Chapter 2 presents a methodology for evaluating model output in order to identify processes, which govern the hydrological behavior of a watershed. In many watersheds, especially in developed countries, this kind of information can be derived from a large amount of observed data. This is not possible in watersheds like the Xiangxi Catchment, where only very basic observed data is available. Chapter 2 addresses **research question 1** by analyzing the applicability of residual analysis as well as the analysis of auto- and cross-correlations for model evaluation in addition to the common model evaluation criteria as a tool to identify important hydrological processes in the Xiangxi Catchment prior to model calibration.

In **Chapter 3**, the basic application of SWAT to the Xiangxi Catchment is presented. The model is set up using the land use map from 1987 and calibrated and validated using the time periods from 1981 through 1986 and 1988 through 1993, respectively. Model performance is evaluated using the common statistical criteria and visual comparison. The most important sources of uncertainty in the model output are discussed in detail, especially with regard to sediment loads at Xingshan Gauge. Thereby, Chapter 3 focuses not only on **research question 2**, but also refers quite extensively to **research question 5**.

The central aim of **Chapter 4** is a preliminary assessment of the impacts of land use change on hydrology and sediment transport in the Xiangxi Catchment. SWAT is used to simulate land use scenarios using the land use maps from 1999 and 2007 as well as three hypothetical land use maps. The impacts of different land use patterns on water balance, streamflow and sediment yield are analyzed at watershed and subbasin level. Chapter 4 mostly focuses on **research question 3**, but the discussion of model uncertainty and thus **research question 5** is revisited shortly and complemented by a few additional aspects.

Chapter 5 presents a detailed analysis of SWAT simulated surface runoff and sediment yield at HRU level. Because of the high fraction of forested areas in most of the subbasins, subbasin averages are not suitable for evaluating the spatial variability of water quality related processes in the Xiangxi Catchment. The HRU level is more appropriate for the identification of Critical Source Areas and targeting Best Management Practices in this watershed. Also, analysis of SWAT output at HRU level can help to check plausibility of model output and identify further sources of uncertainty. Accordingly, Chapter 5 addresses **research questions 4** and **5**.

Chapter 6 summarizes the central findings of this study. A short answer to research questions 1 to 4 is presented, before a summarizing discussion of the most important deficits of the SWAT model setup, parameterization and calibration for the Xiangxi Catchment is presented to answer research question 5. Also, the choice of model is discussed briefly. The implications of the results of this study for land use planning in the Xiangxi Catchment are summarized. Finally, overall conclusions are drawn and an outlook is given, which lists further research needs that were identified in this study.

Chapter 2

Using residual analysis, auto- and cross-correlations to identify key processes for the calibration of the SWAT model in a data scarce region

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Abstract

Hydrological modeling poses a particular challenge in data scarce regions, which are often subject to dynamic change and thus of specific interest to hydrological modeling studies. When a small amount of data available for a catchment is opposed by extensive data requirements by the chosen hydrologic model, ways have to be found to extract as much information from the available data as possible.

In a study conducted in the Xiangxi Catchment in the Three Gorges Region in China, the use of residual analysis as well as auto- and cross-correlations for enhanced model evaluation and for the identification of key processes governing the hydrological behavior of the catchment prior to model calibration was tested. The residuals were plotted versus various variables such as time, discharge and precipitation. Also, auto-correlations were calculated for measured and simulated discharge and cross-correlations of measured and simulated discharge with precipitation were analyzed. Results show that the analysis of residuals as well as auto- and cross-correlations can provide valuable information about the catchment response to rainfall events, which can be very helpful for calibration of hydrologic models in data scarce regions.

2.1 Introduction

In many parts of the world, parameterization and calibration of hydrological models is hampered by a lack of adequate input data (Zhao et al. 2011). But often it is especially those parts of the world, where dynamic change is currently encountered or expected to happen in the future and where modeling studies estimating the impacts of this change on hydrology and water quality are thus indispensable. Therefore, strategies have to be developed to exploit as much information from the available data as possible and find an efficient approach to model parameterization and calibration in data scarce regions (Sivapalan et al. 2003). Often the majority of parameters for complex models have to be roughly estimated (Hörmann et al. 2009). The discrepancy between the low amount of available data on the one hand and the high number of input variables required by many hydrologic models has to be overcome.

The Three Gorges Region in China is an area which is currently facing a large-scale land use change due to the construction of the Three Gorges Dam and the reservoir impoundment. In the Sino-German Yangtze Project (funded by the German Ministry of Education and Research) different aspects of this land use change and its impact on soil erosion, mass movements and diffuse inputs are assessed (Subklew et al. 2010). The chosen study area is the 3,099 km^2 large Xiangxi Catchment. The impact of land use change on the water balance as well as the sediment and phosphorus transport is assessed using the eco-hydrological model SWAT (Arnold et al. 1998). SWAT will be used during further progress of the project to simulate the impact of past, present and future land use patterns on the water balance as well as sediment and phosphorus transport in the catchment. But first of all, the model has to be calibrated in order to represent the hydrology of the Xiangxi Catchment, which is the driving force behind all other processes happening in the watershed. The calibration is hampered by the small amount of data and information available for the Xiangxi Catchment.

Hydrological modeling usually follows a typical workflow. First of all, the model is parameterized using the data available for the respective study area. Second, a sensitivity analysis is carried out to identify the most important model parameters to focus on during calibration and finally, the model is calibrated either manually or using an automated calibration procedure, which has been very popular in recent years (Abbaspour et al. 2007; Bekele and Nicklow 2007; Eckhardt and Arnold 2001; Eckhardt et al. 2005; Green and van Griensven 2008; Muleta and Nicklow 2005; Schuol and Abbaspour 2006; Van Griensven and

Meixner 2007; Zhang et al. 2009). Model evaluation is mostly done by analyzing the simulated versus the measured hydrograph and by using statistical criteria like the Nash-Sutcliffe efficiency (NSE) or the coefficient of determination (R^2).

Another option for model evaluation is residual analysis. This does not only evaluate model performance, but can also help to identify key processes, which govern the catchment response to rainfall events. So far, in the context of hydrological modeling residual analysis has only been used for model evaluation by very few authors (Aitken 1973; Vandewiele et al. 1992; Xu 2001; Feaster et al. 2010). Residuals as well as auto- and cross-correlations are used in this study to identify key processes governing the discharge in the study area prior to model calibration. The main objective is to test whether the analysis of residuals as well as auto- and cross-correlations can be used to support model calibration by allowing conclusions to be drawn with respect to key processes governing catchment behavior.

2.2 Materials and methods

2.2.1 Study area

The Xiangxi Catchment is located in the northwest of Hubei Province in Central China. It covers part of the counties Shennongjia, Xingshan, and Zigui and comprises an area of 3,099 km^2. Originating from the Shennongjia Mountain Nature Reserve in the northwest of the catchment, the Xiangxi River flows in a southward direction over a distance of 94 km until it discharges into the Yangtze River approximately 38 km upstream of the Three Gorges Dam. There are two significant tributaries of the Xiangxi River, the Gufu and the Gaolan Rivers (Figure 2.1).

The Xiangxi Catchment is characterized by large differences in elevation of more than 3,000 m and very steep slopes. The dominating soil types according to Chinese soil classification are Limestone soils and Yellow brown soils, but there are also large areas of Brown soils and Dark brown soils in the high mountain areas and of Purple soils and Yellow soils in the central and southern parts of the catchment. Land use is dominated by forest. Considerable areas of agricultural use can be found in the southern part of the catchment as well as along the rivers and major roads. The mean annual discharge at Gauge Xingshan amounts to 65.5 $m^3 s^{-1}$. The hydrograph of Xiangxi River shows a strong seasonality with high discharge during the summer monsoon and low discharge in winter.

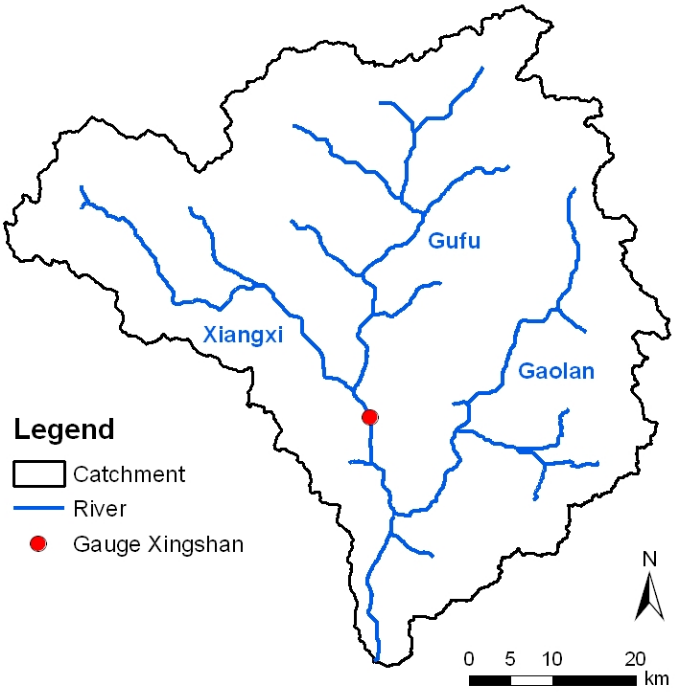

Figure 2.1: The Xiangxi Catchment with the location of Gauge Xingshan

2.2.2 The SWAT model

SWAT (Soil and Water Assessment Tool; Arnold et al. 1998) is an eco-hydrological model, which was developed for modeling the effect of changes in land use and management on the water balance as well as the transport of sediment and agricultural chemicals. It is a continuous time model designed for simulating long periods of time. SWAT has been applied to various catchments all over the world (Arnold and Fohrer 2005; Gassman et al. 2007) and has proven to be a capable tool for assessing the impact of land use change on water quantity and quality (Behera and Panda 2006; Cao et al. 2009; Chaplot et al. 2004; Fohrer et al. 2002; Fohrer et al. 2005; Guo et al. 2008; Heuvelmans et al. 2004; Huisman et al. 2004; Jha et al. 2010; Lenhart et al. 2003; Mishra et al. 2007).

In SWAT, the catchment is divided into subbasins, which are then further subdivided into hydrologic response units (HRU). An HRU is defined by a unique combination of land use, soil, and slope, so it is not identified spatially, but rather a lumped area of all areas with the same combination of land use, soil, and slope (Neitsch et al. 2010).

Simulation of the hydrologic cycle is separated into a land phase and a water phase (Neitsch et al. 2005). The simulation of the land phase is based on the water balance equation, which is calculated separately for each HRU. Moisture and energy inputs needed to drive the hydrologic cycle are provided by the climatic variables precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity. These can be input from measured time series or simulated by the weather generator. Processes taken into account in a HRU include interception, evapotranspiration, infiltration, water movement in the soil profile and runoff. Water can be stored within an HRU in a deep and a shallow aquifer, in the soil profile and in the form of snow. Runoff generated in the HRUs is summed up to calculate the amount of water reaching the main channel in each subbasin (Neitsch et al. 2005). The water phase of the hydrologic cycle describes the routing of runoff in the river channel, using either a variable storage coefficient method (Williams 1969) or the Muskingum routing method.

SWAT allows for detailed management schemes to be defined for each HRU, including time of planting and harvesting, time and amount of fertilizer and pesticides applications, irrigation and grazing. In SWAT2009, the current version of the model, a land use update module was integrated as a new feature to simulate land use change in the subbasins.

2.2.3 SWAT model setup

For this study, SWAT is used in the current version SWAT2009. To set up SWAT for a catchment, the model requires a digital elevation model, a soil map and a land use map as well as climatic data.

The required spatial data was mostly provided by the project partners of the YANGTZE-Project. The Digital Elevation Model (DEM) was downloaded from the SRTM database (Jarvis et al. 2008), where it is available with a resolution of 90 m x 90 m. The soil map was digitized from analogue soil maps of the counties Shennongjia, Xingshan and Zigui on a scale of 1:160000/1:180000, which were mapped during the Second National Soil Survey in China (Schönbrodt et al., submitted). The corresponding soil parameters of the soil types occurring in the Xiangxi Catchment were obtained from internet and literature resources (China Scientific Soil Database 2010; Guo et al. 2008; Schönbrodt et al. 2010). A total of three land use maps classified from Landsat images is available for the years 1987, 1999 and 2007 (Seeber et al. 2010).

One climate station located within (Xingshan) and two climate stations located just outside the catchment (Shennongjia and Zigui) are implemented in the model. For all three stations long-term records are available for precipitation, temperature, humidity and wind speed. Solar radiation was calculated from sunshine duration. The statistics used by the weather generator to simulate missing climate data were calculated using the time series of station Xingshan.

The model is run on a daily time step for the years 1985 to 1993, but only the last six years are used for calibration, while the first three years are used as warm-up period. SWAT has not been calibrated for the Xiangxi Catchment yet. The data used for this study are the results of the initial SWAT model run.

2.2.4 Model evaluation

Most commonly, evaluation of hydrologic models is done by comparing the simulated and the measured hydrographs or flow duration curves graphically and using one or more statistical criteria, e.g. the NSE (Nash-Sutcliffe efficiency; Nash and Sutcliffe 1970), the PBIAS (Percent bias; Gupta et al. 1999) or the RSR (RMSE-observations standard deviation ratio). The statistical criteria give an overall performance rating for the simulation, but all information on the characteristics of the hydrograph is lost due to evaluating the whole time series using just one single value.

Residuals are the differences between the measured and simulated values. This means that negative residuals indicate an overestimation of discharge by the model, while positive residuals indicate an underestimation. Residuals can be analyzed without losing the time reference of the data, which allows for the consideration of seasonal effects. Also, it is possible to examine specific parts of the hydrograph separately, like for example the rising limb and the recession curve or high and low flows. In spite of the diverse possibilities offered for model evaluation by residual analysis, it is not very commonly used in hydrological modeling. Nevertheless, residual analysis has been included in model evaluation by a few authors (Aitken 1973; Feaster et al. 2010; Vandewiele et al. 1992; Xu 2001). In this study, residual analysis is not used to check whether the residuals behave as required by the model hypotheses, but it is rather used as a tool to get as much information out of the available data as possible before starting to calibrate the model. Therefore, the residuals are plotted versus different important variables like time, runoff and precipitation.

Also, the auto-correlations of measured and simulated discharge and the cross-correlations of measured and simulated discharge with precipitation are calculated and analyzed in order to identify possible shortcomings in the representation of runoff processes in the model.

2.3 Results and discussion

2.3.1 Common model evaluation

The hydrograph and the statistical criteria give a good idea of the overall model performance. The hydrograph indicates that the simulated discharge fits the measured discharge reasonably well (Figure 2.2). This is also confirmed by the Nash-Sutcliffe efficiency, the PBIAS, and the R^2, which are 0.42, 42.1, and 0.63, respectively. Even though the statistical criteria are not in the range considered as satisfactory by Moriasi et al. (2007), they are quite satisfactory when taking into account that the model has not been calibrated yet. Nevertheless, there is definitely room and need for improvement of the simulated hydrograph.

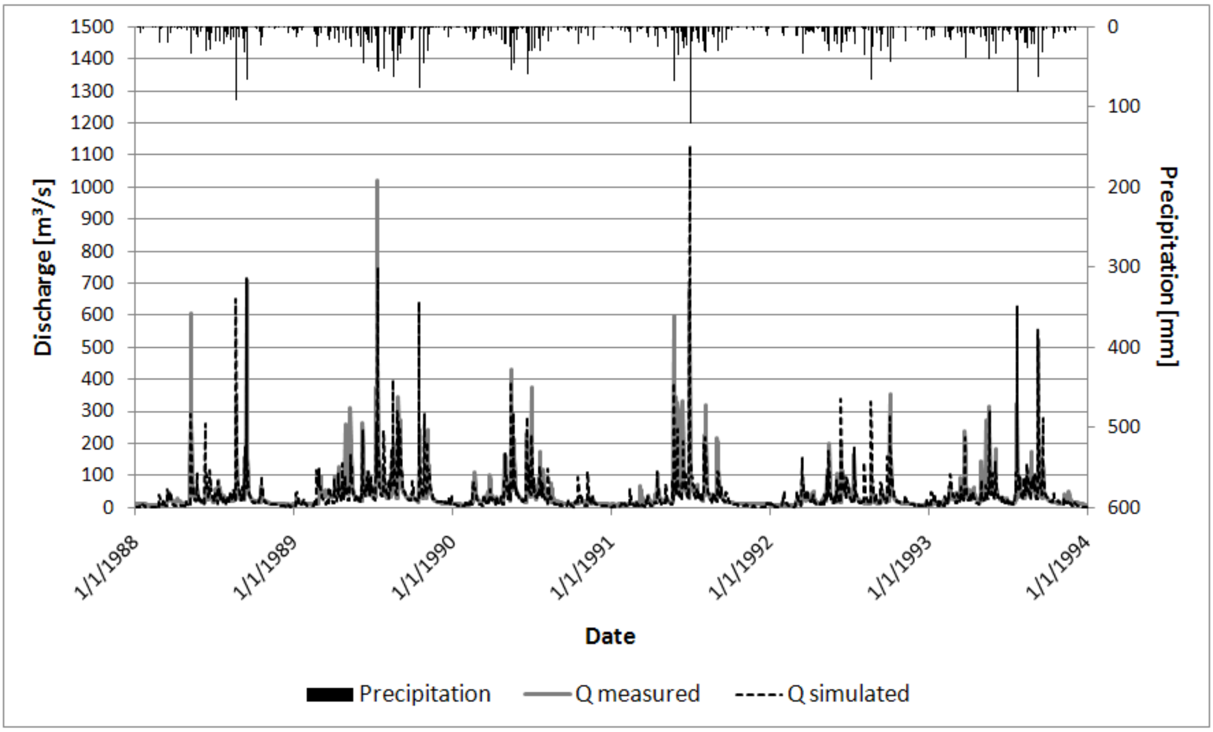

Figure 2.2: Time series of measured versus simulated discharges at gauge Xingshan during the calibration period

The flow duration curve (Figure 2.3) shows that discharge which is exceeded up to 0.5% and between 5.5 and 25% of the time is slightly overestimated by the model, whereas discharge which is exceeded 0.5 to 5.5% and more than 70% of the time is slightly underestimated. The flow duration curve gives some valuable information which is not as obvious from the hydrographs (Figure 2.2) and which is not given by the statistical criteria. But still it is not possible to draw any conclusions with regard to the processes responsible for the differences between measured and simulated discharge. The analysis of residuals as well as auto- and cross-correlations can be used in this context to extend model evaluation and at the same time it can provide hints how to improve the parameterization of the model.

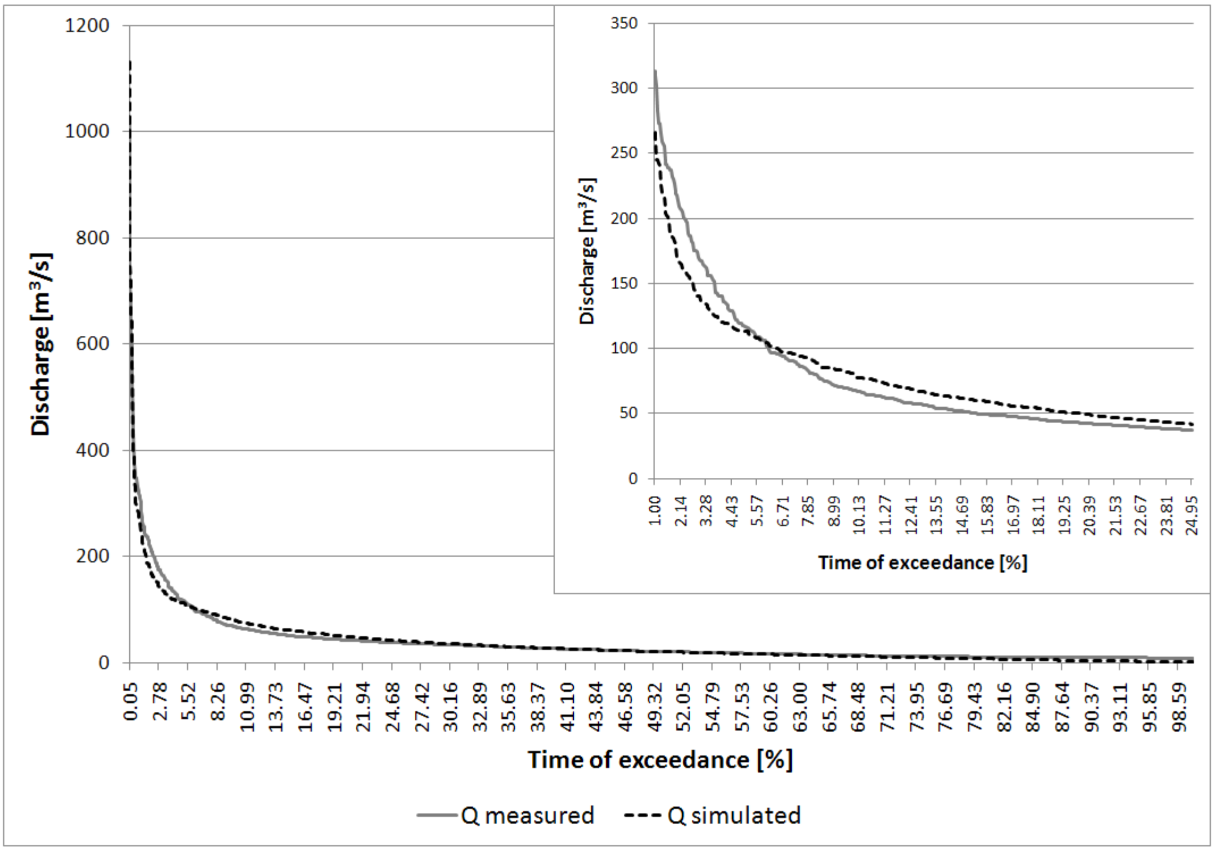

Figure 2.3: Flow duration curves for measured and simulated discharges at gauge Xingshan during the calibration period

2.3.2 Residual analysis

The six-year calibration period comprises a total of 2,192 days. Discharge is overestimated by the model on 829 days as indicated by the negative residuals and underestimated on 1,362 days as indicated by the positive residuals.

Figure 2.4 shows that there is some seasonality in the residuals. The largest residuals occur in summer. This can be explained by the influence of the summer monsoon, which brings about frequent and heavy precipitation events and accordingly high discharges. The residuals indicate that the peaks are not simulated very well by the model yet. Nevertheless, there is no clear trend towards positive or negative values, which indicates that some model variable causes it to overestimate discharge in certain situations and to underestimate it in others. Here a more detailed analysis of processes will be required in order to identify the factors governing the formation of high discharges. Both positive and negative outliers and extreme values are visible. Also, the range without outliers is quite large in summer while it is much smaller during the low flow period in winter, when residuals are lower and mostly tend towards slightly positive values. It is important to keep in mind that low absolute residuals might still be very high when related to the measured discharge. Therefore the simulated data might not fit the measured data very well during low flow periods even though the comparatively small residuals suggest the opposite.

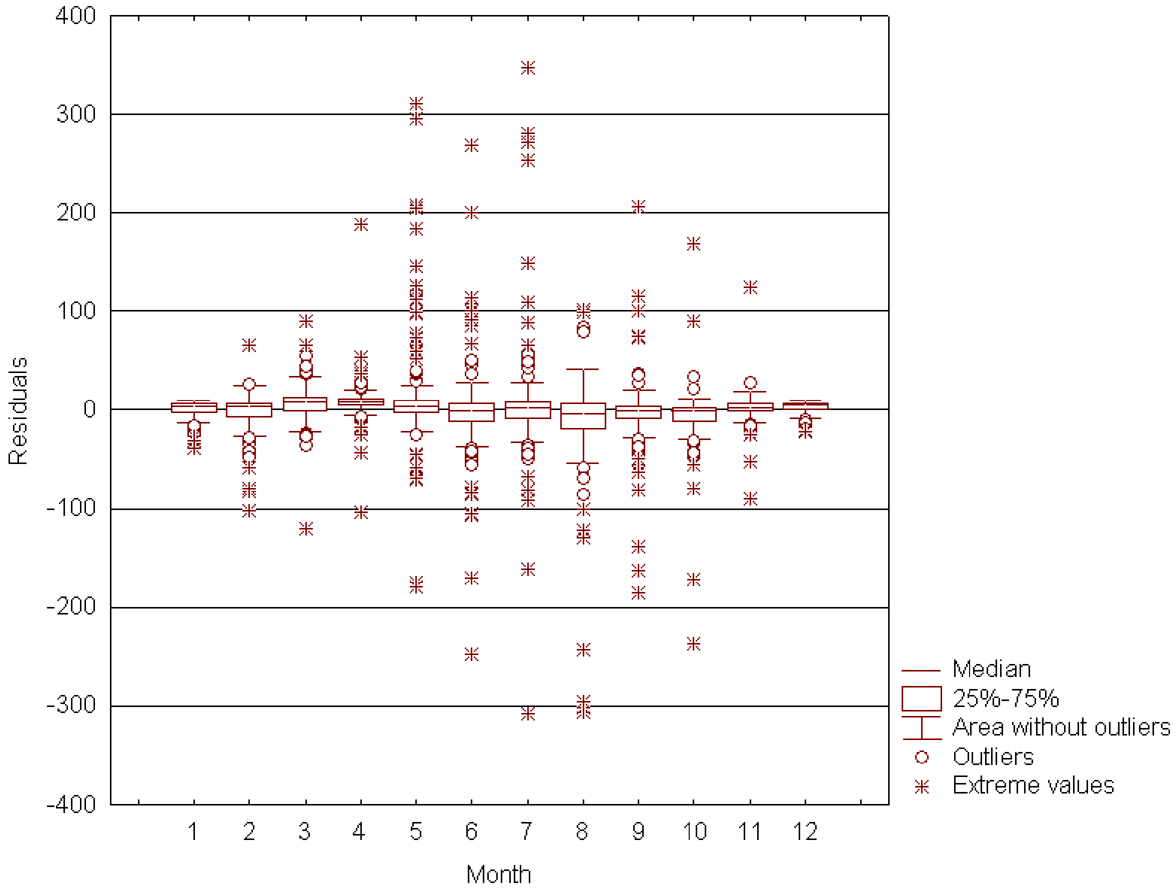

Figure 2.4: Box-and-Whisker plot for residuals per month

The relative deviations plotted in Figure 2.5 reveal that the largest relative differences between measured and simulated discharge occur during smaller flood events, especially following a low flow period. In certain cases, the simulated discharge reacts to precipitation events while there is no change in the observed discharge, while in other cases, there is a timing error and the simulated peak occurs one or two days earlier than the observed peak. This suggests that the variability of precipitation in the Xiangxi Catchment is not represented very well by the available climate data. In SWAT, each subbasin is assigned the precipitation data measured at the climate station closest to its center. Therefore, the data measured at climate station Xingshan is assumed to be valid for large parts of the catchment and local rainfall events can have a much higher impact on simulated discharge than they had on discharge in reality. This stresses the importance of representative climate data, especially in mountainous catchments.

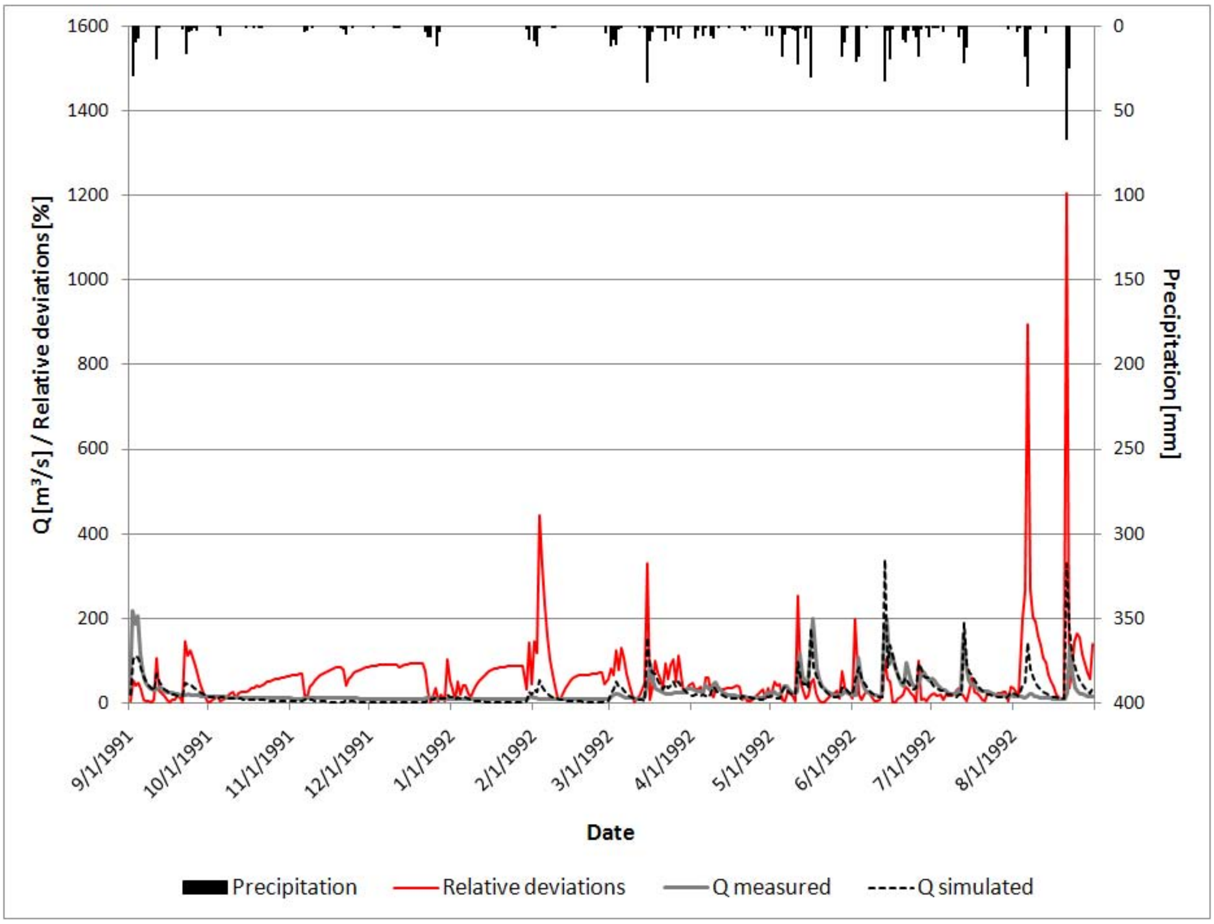

Figure 2.5: Relative deviations of simulated discharge from measured discharge (%), measured and simulated discharge (m^3 s^{-1}) and precipitation (mm) during the time period from 1 September 1991 to 31 August 1992

The relative deviations tend to increase during the low flow period in winter, which is due to a slow decrease of simulated discharge while the measured discharge stays more or less stable (Figure 2.5). This suggests the existence of some kind of storage volume in the Xiangxi Catchment, which is not yet accounted for in the model. Possible storage volumes slowly releasing water during the winter can be the terraced slopes or two reservoirs along Gufu River, one of the main tributaries of Xiangxi River.

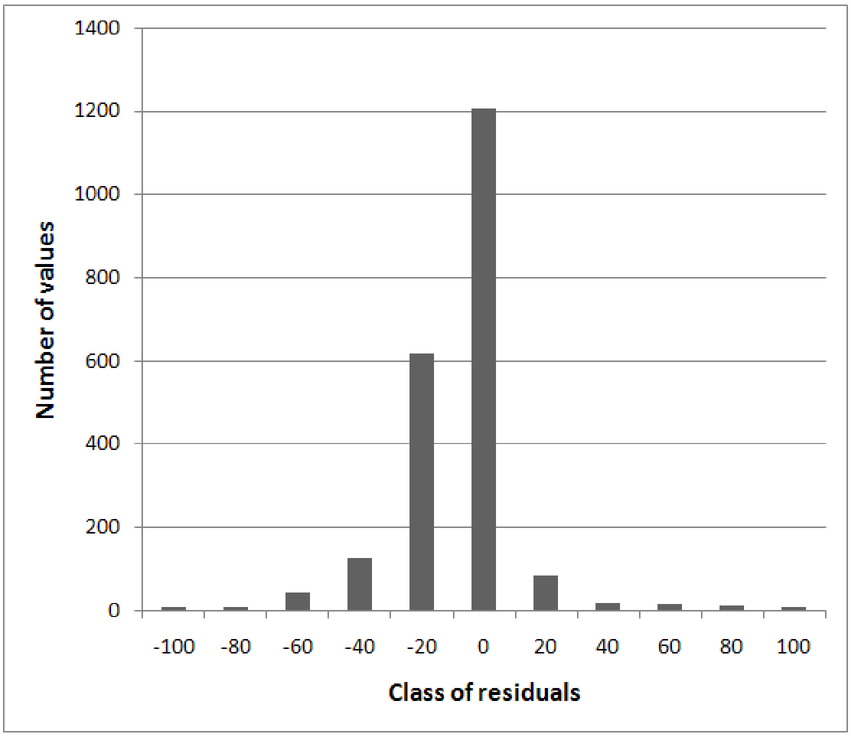

Figure 2.6: Number of values in each class of residuals (classes named according to their lower boundary)

The relationship between the residuals and the measured discharge is shown in Figure 2.7. To improve visualization, the residuals are grouped in classes and only values within the range from -100 to 120 $m^3 s^{-1}$ are included. This range comprises 2,147 out of 2,192 values and thus the majority of all residuals. Most of the residuals larger than -100 or 120 $m^3 s^{-1}$ are outliers corresponding to extreme discharge peaks. The number of values in each class is shown in Figure 2.6. The class labels in Figure 2.6 and Figure 2.7 indicate the lower boundary of each class. For both positive and negative residuals the number of values within each class decreases with increasing residuals (Figure 2.6). Apart from this, there is a clear difference visible between negative and positive residuals. Except for a few outliers and extreme values, negative residuals, i.e. overestimations of discharge by the model, are mainly associated with relatively low measured discharges between 0 and 100 $m^3 s^{-1}$ and there is no clear trend visible. In contrast, the positive residuals show a distinct increasing trend with increasing discharge volumes. The lower the measured discharge the lower is also the underestimation of discharge by the model. Strong underestimations of discharge ranging from 60 to 120 $m^3 s^{-1}$ occur only for discharges higher than 100 $m^3 s^{-1}$. Discharges lower than 100 $m^3 s^{-1}$ are underestimated by at most 60 $m^3 s^{-1}$. There are very few outliers and extreme values of discharge and the majority of residuals are lower than 20 $m^3 s^{-1}$. The positive residuals indicate a systematic error in the simulation of discharge peaks, which might be due to an inappropriate representation of the fast runoff components.

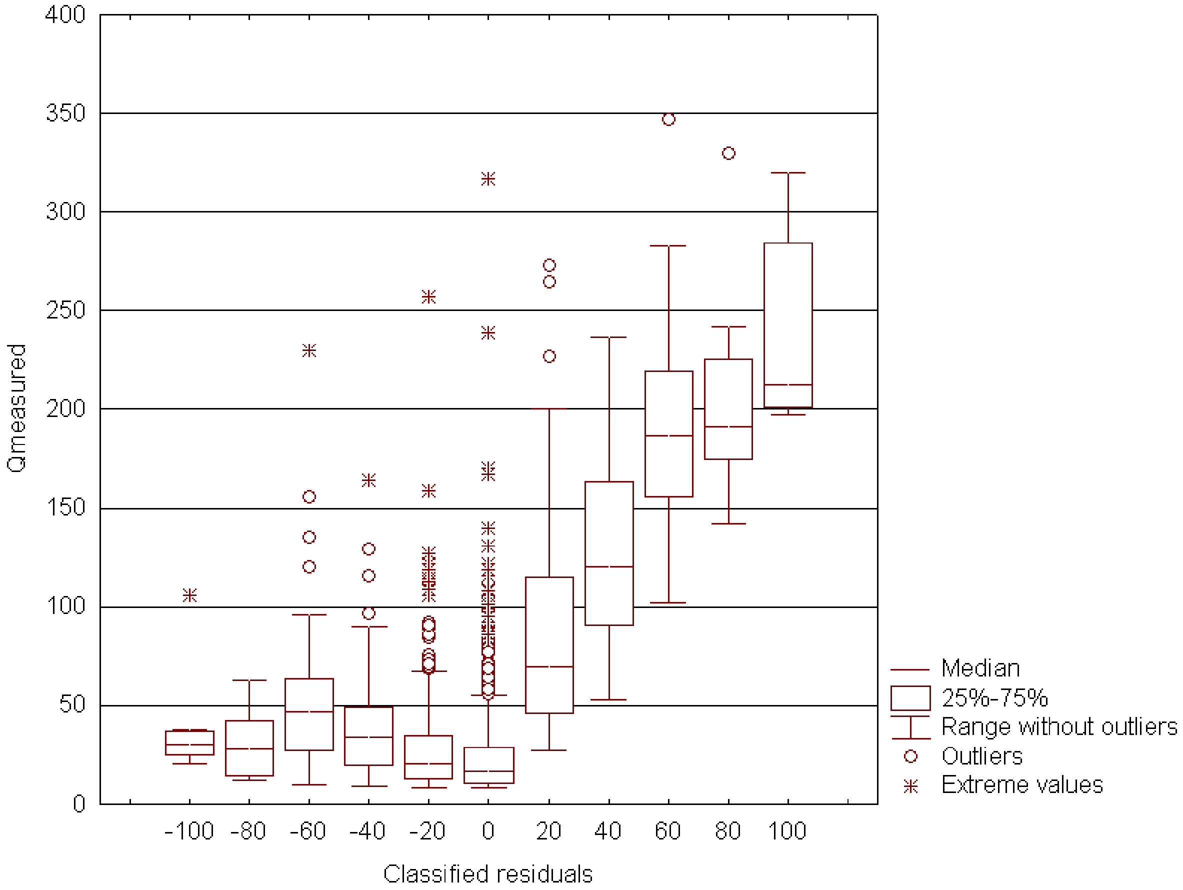

Figure 2.7: Box-and-Whisker plot for measured discharge versus classified residuals (classes named according to their lower boundary)

2.3.3 Analysis of auto- and cross-correlations

The comparison of the auto-correlations of measured and simulated discharge reveals an important difference between the measured and the simulated time series (Figure 2.8). For a time lag of one day, the measured discharge is stronger auto-correlated than the simulated discharge, i.e. the measured discharge on a certain day is more dependent on the discharge on the day before than the simulated discharge.

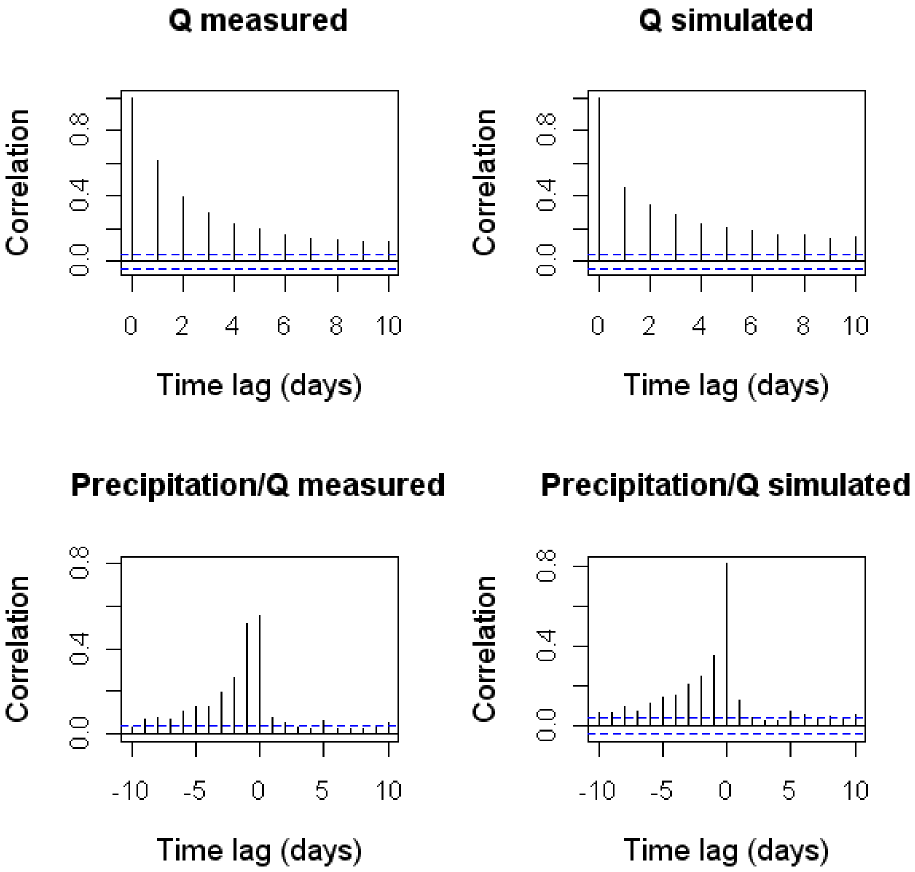

Figure 2.8: Autocorrelations of measured discharge and simulated discharge and cross correlations of precipitation with measured and simulated discharge

This indicates that the measured discharge is influenced by slower runoff components than the simulated discharge. Therefore, the underestimation of discharge by the model is probably rather caused by too little lateral or groundwater flow than by an insufficient amount of surface runoff as assumed before. The calibration of parameters governing slow runoff components in SWAT might thus improve the simulation of peaks considerably. This assumption is supported by the cross-correlations of measured and simulated discharge with precipitation, which show a distinct difference as well (Figure 2.8). While the simulated discharge is much more dependent on the precipitation on the same day than the measured discharge, it is much less dependent on the precipitation on the previous day. This again suggests a stronger influence of fast runoff components in the simulation compared to the observation and thus a need to calibrate parameters governing slower runoff components in order to slow down the catchment's response to precipitation events in the model.

2.4 Conclusions

The study has shown that the analysis of residuals as well as auto- and cross-correlations can be valuable tools for model evaluation. While the comparison of the measured and the simulated hydrographs and the calculation of statistical criteria provide a good evaluation of the overall performance of the model, they do not allow any conclusions with regard to the key processes governing the catchment hydrology and explaining the shortcomings of simulated discharge. These have to be identified for model calibration. In regions where a sufficient amount of adequate data is available the required information can often be derived from the observed data. As this is not possible in data scarce regions, other ways of acquiring the required knowledge have to be found. In this context residual analysis as well as the analysis of auto- and cross-correlations can be used as a tool to improve understanding of key processes in a catchment.

In this paper, only a selection of possible variable interrelations is presented. A closer analysis of residuals might include the impact of further variables on residuals, e.g. evapotranspiration, surface runoff and groundwater runoff. Also, the residuals have not yet been analyzed separately for different parts of the hydrograph like the rising and the falling limb or high and low flows. Nevertheless it has been shown that residual analysis can be used to identify key processes in a catchment of interest. A more detailed analysis of residuals including more variables and evaluating specific parts of the hydrograph separately could provide further insights to the characteristics of the catchment, which have to be considered during model calibration. Especially when combined with sensitivity analysis, by which the most important model parameters are identified, the analysis of residuals as well as auto- and cross-correlations can be useful tools for model calibration.

2.5 Acknowledgements

The authors would like to thank the German Federal Ministry of Education and Research (BMBF, No. 03 G 0669) for funding the Sino-German Yangtze Project. Special thanks also go to the Research Centre Jülich for the project coordination and to the project partners from Tübingen and Giessen University for providing the spatial input data required by SWAT.

Chapter 3

Simulation of streamflow and sediment with the SWAT model in a data scarce catchment in the Three Gorges Region, China

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Abstract

The Three Gorges Region in China is currently subject to a large-scale land use change, which was induced by the construction of the Three Gorges Dam on the Yangtze River. The relocation of towns, villages, and agricultural areas is expected to impact the water balance and increase erosion rates and sediment yields in the affected catchments. Hydrologic and water quality models are frequently used to assess the impact of land use changes on water resources. In this study, the eco-hydrological model SWAT is applied to the Xiangxi Catchment in the Three Gorges Region. This paper presents the calibration and validation of streamflow and sediment loads at Xingshan gauging station. The calibration of daily streamflow resulted in a satisfactory fit of simulated and observed data, which is indicated by NSE (Nash-Sutcliffe efficiency) values of 0.69 and 0.67 for the calibration (1981-1986) and validation (1988-1993) periods, respectively. In contrast, the model was not able to simulate the monthly average sediment loads correctly as indicated by very low NSE values of 0.47 (calibration) and 0.08 (validation). This might be due to a number of reasons including an inadequate representation of spatial rainfall variability by the available climate stations, insufficient input data, uncertainties in the model structure, or uncertainties in the observed sediment loads. The discussion of these possible reasons for the incorrect prediction of sediment loads by SWAT reveals the need for further research in the field of hydrological and water quality modeling in China.

3.1 Introduction

The construction of the Three Gorges Dam on the Yangtze River has induced a large scale land use change in the Three Gorges Region in Central China. The most important driver of this land use change is the inundation of agricultural areas, towns and villages (Seeber et al. 2010), which forced people to resettle and relocate their cropland from the fertile valley bottoms to steeply sloping uphill areas with shallow soils characterized by a poor structure and low organic matter contents (Shi et al. 2004). This is expected to influence not only the water balance in the affected catchments, but also the diffuse inputs of sediment to rivers due to an increase in erosion. Having a direct effect on evapotranspiration (ET) and runoff generation, as well as sediment yield, changes in land use can impact water supply and water quality considerably (Chaplot et al. 2004; Fohrer et al. 2001; Mishra et al. 2007). Erosion and non-point source pollution of rivers with sediment and nutrients are the major environmental problems in the Three Gorges Region (Heggelund 2006; Shen et al. 2010a; Tian et al. 2010), for which Shi et al. (1992) estimated an annual soil loss of 157 million tons and an annual sediment delivery to the Yangtze of 41 million tons. The risk of erosion is expected to increase considerably due to recent and future changes in land use (Lu and Higgitt 2000; Meng et al. 2001; Schönbrodt et al. 2010).

High soil erosion rates and sediment inputs can lead to sedimentation in the Three Gorges Reservoir and thus impact its operation and life span (Higgitt and Lu 2001; Shi et al. 2004). Also, a higher risk of reservoir eutrophication can be expected because of increasing inputs of nutrients, especially phosphorus, adsorbed to sediment and due to reduced flow velocities and prolonged residence times of water in the reservoir (Dai et al. 2010; Zeng et al. 2006). Additionally, sediment deposited in the reservoir might desorb large amounts of phosphorus (Wang et al. 2009) and thereby further increase the eutrophication risk. Since the impoundment of the Three Gorges Reservoir started, algae blooms have been frequently observed, especially in the backwater areas of tributaries of the Yangtze River (Li et al. 2008; Xu et al. 2011b; Ye et al. 2007; Zeng et al. 2006; Zhong et al. 2005; Zhang et al. 2010a).

It is important to assess and quantify the impact of changes in land use and management on the water quantity and quality of the catchments affected by the impoundment of the Three Gorges Reservoir and to develop sustainable land use scenarios in order to mitigate the negative effects of the Three Gorges Project. Because the possibilities to conduct field experiments are limited, hydrologic and water quality models are valuable tools and often the only feasible way of evaluating land use change and management scenarios (Ahl et al. 2008; Arabi et al. 2006; Behera and Panda 2006; Fohrer et al. 2001). The use of models not only facilitates the quantification of the impacts of land use and management on water quantity and quality, but also the identification of hot-spots within a watershed where the implementation of measures to improve the status of water resources needs to focus on (Chaubey et al. 2005).

Among the numerous hydrologic and water quality models that have been developed in recent years, the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998) is one of the most suitable models for simulating water and sediment yields under land use and management scenarios (Behera and Panda 2006). It has been successfully applied to watersheds all over the world, not only for hydrological simulations, but also for the assessment of sediment and nutrient transport in watersheds (Arnold and Fohrer 2005; Gassman et al. 2007). According to Gassman et al. (2007) more than 40 studies have been performed using SWAT in China, although only a few of these included predictions of sediment yields and transport (Cheng et al. 2007; Hao et al. 2004; Ouyang et al. 2008, 2010; Shen et al. 2009, 2010a; Xu et al. 2009; Yang et al. 2009; Zhang et al. 2003).

Before simulating land use or land management scenarios, a model needs to be properly calibrated and validated against observed data in order to avoid incorrect predictions (Behera and Panda 2006; Chu et al. 2004). This can be a challenging task, especially in data-scarce catchments, where time series of observed data are often only available in an insufficient temporal and/or spatial resolution (Zhao et al. 2011). Even constructing the model can be difficult if the spatial data sets of topography, hydrography, land use, and soils are of coarse resolution and variable quality. As stated by Chaplot (2005), the quality of the simulation output depends strongly on the quality of representation of catchment characteristics by the spatial input data.

In this study, SWAT is applied to the Xiangxi Catchment in Hubei Province, which is taken as an example for catchments heavily influenced by the impoundment of the Three Gorges Reservoir. Specific objectives of this study were to: (1) evaluate the performance of SWAT in simulating streamflow and sediment transport in a data-scarce mountainous catchment in the Three Gorges Region in Central China and (2) to calibrate and validate the model in order to provide a sound basis for the simulation of land use scenarios.

3.2 Materials and methods

3.2.1 Study area

The Xiangxi Catchment comprises an area of 3,200 km^2 and is located in Hubei Province in Central China (Figure 1). It extends over Xingshan County as well as parts of Shennongjia and Zigui Counties. It is characterized by large differences in elevation, ranging from 3,078 m.a.s.l. near the source of the Xiangxi in the Shennongjia Mountains to 62 m.a.s.l. at the mouth of the Xiangxi, which is located approximately 40 km upstream of the Three Gorges Dam (TGD). With a mean gradient of 24° and a maximum gradient of 76° slopes in the catchment are very steep. The Xiangxi is 94 km long and has two large tributaries, the Gufu and the Gaolan (Figure 3.1). Mean annual streamflow (1970-2005), measured at Xingshan gauging station in the centre of the catchment, amounts to 36.75 m^3 s^{-1}. Mean annual temperature and precipitation at Xingshan climate station (1961-1990) are 16.9°C and 1,000 mm, respectively. The climate in the Xiangxi Catchment is strongly influenced by the subtropical summer monsoon, which entails a distinct seasonality of precipitation and streamflow with very high amounts in summer and much lower amounts in winter. Temperature and precipitation are additionally influenced by the mountainous topography and vary considerably with altitude (He et al. 2003).

The dominant soil types in the catchment are Limestone soils and Yellow-brown soils (Genetic Soil Classification of China). According to a land use map classified from a Landsat image for the year 1987 (Seeber et al. 2010) more than 80% of the Xiangxi Catchment was covered by forest. Larger areas of farmland and orchards were located primarily along the rivers and roads, so due to their strong connectivity to the rivers they are expected to have impacted diffuse inputs considerably, even though they only accounted for 13.2% and 1.7% of the catchment, respectively. Covering only 0.2% of the Xiangxi Catchment, urban areas were of minor importance (Seeber et al. 2010). In the higher mountain areas, tea is planted as a cash crop (He et al. 2003), but could not be distinguished from forest in the land use classification conducted by Seeber et al. (2010) (C. Seeber, personal communication, 2009).

Since the Three Gorges Dam was closed and the reservoir impoundment started in 2003, the Three Gorges Reservoir has been expanding progressively into Xiangxi River, transforming its lower 30 km into a narrow bay characterized by reduced flow velocities and submerging an area of 9,700 ha, including cropland, woodland, and residential areas (Guo et al. 2003).

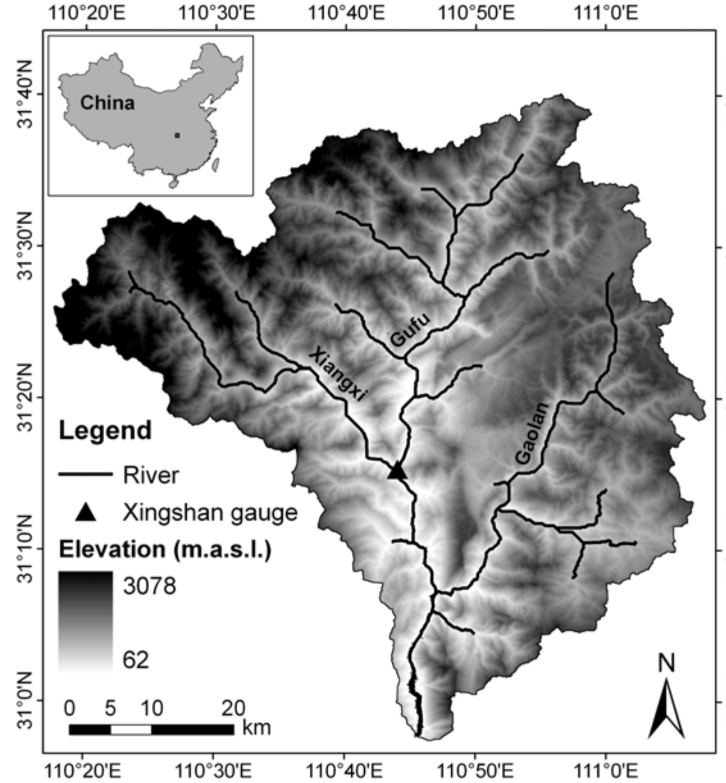

Figure 3.1: The Xiangxi Catchment and its location in China

3.2.2 The SWAT model

SWAT (Arnold et al. 1998) is an eco-hydrological model, which was developed to predict the impact of land use and land management practices on water, sediment, and agricultural chemical yields in large watersheds. It is a continuous time model designed for simulating long periods of time (Arnold et al. 1998; Arnold and Fohrer 2005; Neitsch et al. 2011).

In SWAT, the catchment is divided into subbasins, which are then further subdivided into hydrological response units (HRUs). These are lumped areas within a subbasin with a unique combination of slope, soil type, and land use.

Simulation of the hydrologic cycle is separated into a land phase and a water phase (Neitsch et al. 2011). The simulation of the land phase is based on the water balance equation, which is calculated separately for each HRU. Moisture and energy inputs needed to drive the hydrologic cycle are provided by the climatic variables precipitation, maximum and minimum temperature, solar radiation, wind speed, and relative humidity. These can be input from observed time series or simulated by a weather generator. Processes taken into account in an HRU include interception, evapotranspiration, infiltration, water movement in the soil profile and runoff. Water can be stored within an HRU in a deep and a shallow aquifer, in the soil profile and in the form of snow. Runoff generated in the HRUs is summed up to calculate the amount of water reaching the main channel in each subbasin (Neitsch et al. 2011). The water phase of the hydrologic cycle describes the routing of runoff in the river channel, using either a variable storage coefficient method (Williams 1969) or the Muskingum routing method (Linsley et al. 1958).

Sediment yield is estimated for each HRU using the Modified Universal Soil Loss Equation (MUSLE; Williams 1975). Sediment routing in the channel is controlled by two processes, degradation and deposition, with deposition occurring when the upland sediment load is larger than the transport capacity of the channel and degradation occurring when it is smaller. The transport capacity of a channel segment is calculated as a function of the peak channel velocity (Arnold et al. 1995).

SWAT allows for detailed management schemes to be defined for each HRU, including time of planting and harvesting, time and amount of fertilizer and pesticides applications, irrigation, and grazing. In SWAT2009, the current version of the model, a land use update module was integrated as a new feature to simulate land use change in the subbasins.

3.2.3 Available input data

For the model setup, SWAT requires spatial input data including a digital elevation model (DEM), a land use map and a soil map. The Digital Elevation Model (DEM) was obtained from the SRTM database (Jarvis et al. 2008), where it is available with a resolution of 90 x 90 m. The soil map was digitized from analogue soil maps of the counties Shennongjia, Xingshan and Zigui on a scale of 1:160,000/1:180,000, which were mapped during the Second National Soil Survey in China (Schönbrodt et al. 2011). The corresponding soil parameters of the soil types occurring in the Xiangxi Catchment were obtained from internet and literature resources (China Scientific Soil Database 2010; Guo et al. 2008; Schönbrodt et al. 2010). The land use map used in this study was classified from a Landsat-TM scene from 1987 with a resolution of 30 x 30 m (Seeber et al. 2010). The Level 1 classification was performed according to the Chinese National Standard of Land Use Classification (Chen and Zhou 2007), resulting in a total of 7 land use classes.

Climate data are available for three stations, of which only one (Xingshan) is located within the Xiangxi Catchment, while the remaining two (Shennongjia and Zigui) are located outside the catchment borders. Nevertheless they are situated close enough to the catchment to be considered by the model. For all three stations, long-term time series are available for precipitation, temperature, wind speed, humidity and sunshine duration. The data on sunshine duration was used to estimate solar radiation based on a method developed by Bahel et al. (1987). A daily time series of streamflow at the gauging station Xingshan is available from 1970 to 2005, although data for the years 1975 and 1987 are missing. Daily sediment data for the gauging station Xingshan is available from 1970 to 1986 with data for the year 1975 missing as well. However, the exact technique and timing of the sediment sampling is not known (T. Jiang, personal communication, 2010). It is assumed that the daily sediment loads were calculated based on observed daily streamflow and sediment concentrations.

3.2.4 Model setup and calibration

For this study, SWAT was used in its current version SWAT2009 (Revision 477). Based on the DEM, the Xiangxi Catchment was divided into 37 subbasins. An additional subbasin was created when adding an outlet at the location of Xingshan gauging station, so the watershed delineation resulted in a total of 38 subbasins. These were subdivided into 792 HRUs. In order to maintain a reasonable model run time, the number of HRUs was restricted by setting thresholds for land use, soil, and slope classes of 2, 10, and 10%, respectively. Because of these thresholds, minor land use, soil, and slope classes within a subbasin were eliminated during HRU definition.

For the calculation of potential evapotranspiration (PET), the Penman-Monteith equation (Monteith 1965) was chosen. The rainfall-runoff routing is computed using the SCS curve number method (USDA Soil Conservation Service 1972) and the channel routing is calculated according to the variable storage coefficient method (Williams 1969). At the current stage of the study there is only little information available about crop rotations, fertilization, and tillage, so management schedules were kept very simple. Nevertheless it was ensured that all crops and plants showed a reasonable development of biomass and leaf area index. Plant parameters for oranges [*Citrus aurantium*] and tea [*Camellia sinensis*] (J.R. Kiniry, personal communication, 2011) as well as rapeseed [*Brassica napus*] were added to the crop database in SWAT. The crops planted on agriculturally used areas in the Xiangxi Catchment are very diverse and alternate on a small scale. This is not possible to implement in the model, because firstly the resolution of the available land use map is too coarse to capture the small scale pattern of crops and secondly SWAT does not allow for more than one crop growing in an HRU at the same time. Therefore, all agricultural areas in the catchment are represented by a rapeseed and corn [*Zea mays*] rotation with rapeseed growing during the cold season and corn growing during the warm season.

Table 3.1: Parameters used for the calibration of streamflow at Xingshan gauging station and their initial and final values

Input file	**Parameter**		**Initial value**	**Final value**
	Name	**Description**		
Basin	ESCO	Soil evaporation compensation factor	0.95	0.1
	SURLAG	Surface runoff lag coefficient	4	1.58
Management	CN2	Initial SCS runoff curve number for moisture condition II	varying†	+20%
Soil	SOL_AWC	Available water capacity of the soil layer, mm H_2O mm^{-1} soil	varying ‡	+13.5%
	SOL_K	Saturated hydraulic conductivity, mm h^{-1}	varying ‡	+22.5%
	SOL_Z	Depth from soil surface to bottom of layer, mm	varying ‡	-14.7%
Groundwater	GW_DELAY	Groundwater delay time, d	31	10
	ALPHA_BF	Baseflow alpha factor, d	0.048	0.014
	GW_REVAP	Groundwater “revap” coefficient	0.02	0.2
Channel routing	CH_K2	Effective hydraulic conductivity in main channel alluvium, mm h^{-1}	0	50
	CH_N2	Manning’s n value for the main channel	0.014	0.01
	ALPHA_BNK	Baseflow alpha factor for bank storage, d	0.048	1

† Initial values vary according to the land use class
‡ Initial values vary according to soil type and layer

As the spatial density of climate stations is very low in the Xiangxi Catchment and all three climate stations used by SWAT are located on elevations below 1,000 m, changes of precipitation with elevation are not represented very well. Therefore, elevation bands were implemented in the model as proposed by Fontaine et al. (2002) by entering the average elevation of up to seven elevation band and the percentage of the subbasin area within that band in each of the 38 subbasin input files. A temperature lapse rate of 6°C and a precipitation lapse rate of 320 mm were specified.

Calibration of streamflow and sediment was carried out manually and included parameters from the basin, subbasin, HRU, management, soil, groundwater and the channel routing input files. Table 3.1 lists the calibrated parameters with their initial and final values. For the streamflow calibration, a six-year time period from 1981 to 1986 was used, encompassing wet, dry, and average years. Streamflow was validated using the six-year time period from 1988 to 1993. Sediment calibration and validation was carried out for the years 1981 to 1983 and 1984 to 1986, respectively. While streamflow was calibrated and validated on a daily time step, monthly values were used for sediment calibration and validation. The model was run with a four-year warm-up period from 1977 to 1980.

3.2.5 Model evaluation

As suggested by Moriasi et al. (2007), hydrographs of observed and simulated daily streamflow, sediment graphs of observed and simulated monthly loads at Xingshan gauging station as well as a number of statistical techniques were used for model evaluation.

Legates and McCabe (1999) recommend using the Nash-Sutcliffe efficiency (NSE) in combination with one or more absolute error statistics like the mean absolute error (MAE) or the root mean square error (RMSE). Additionally, the percent bias (PBIAS) and the coefficient of determination (R^2) are used for model evaluation in this study to improve the comparability to other studies. Even though streamflow was calibrated against daily observed data, monthly statistics are reported as well in order to enable the rating of model performance according to the general performance ratings proposed by Moriasi et al. (2007) for a monthly time step.

As widely acknowledged, a good correlation between observed and simulated time series at the watershed outlet or any other single gauge within the catchment is not sufficient to validate a physically based model (Arabi et al. 2006; Beven 1989). Therefore, the apportionment of rainfall into evapotranspiration (ET) and water yield as well as the allocation of runoff to different pathways was evaluated in addition to the analysis of the time series of streamflow at Xingshan gauging station. To compare the proportions of different runoff pathways, an automated digital filter technique (Arnold and Allen 1999) was used to separate baseflow from surface runoff for both observed and simulated streamflows.

3.3 Results and discussion

3.3.1 Streamflow and water balance

The calibration and validation of streamflow at Xingshan gauging station resulted in a good fit of simulated and observed data, which is confirmed both by the visual comparison of the hydrographs and by the model evaluation statistics (Figure 3.2, Table 3.2). Before model calibration the mean of simulated data was considerably lower than the mean of observed data. By implementing the elevation bands in the model, the amount of water available for runoff was increased resulting in a very low average error of 2.52 $m^3\ s^{-1}$ during the calibration period and a slightly higher average error of 6.70 $m^3\ s^{-1}$ during the validation period. As shown by the hydrographs in Figure 3.2, the timing and the recession of streamflow peaks is simulated quite well, but the maximum flow volume of most peaks is underestimated. Only very few streamflow peaks are overestimated by the model. The simulated streamflow matches the observed streamflow reasonably well during the low flow periods in winter, even though it is characterized by a stronger reaction to small precipitation events. This explains the general overestimation of mean streamflow in spite of the underestimation of most streamflow peaks, which is indicated by the average error and the PBIAS values (Table 3.2).

The incorporation of elevation bands allowed for an increase of the general amount of precipitation in order to account for increases in precipitation with elevation, but naturally there is still a strong link to the data observed at the climate stations. Therefore, precipitation events, which only occurred locally at the climate stations, are assigned to the whole catchment leading to overestimations of streamflow peaks, while precipitation events occurring locally in remote parts of the catchment are not captured by the climate stations, leading to underestimations of streamflow peaks. When comparing the timing and magnitude of streamflow peaks to those of the precipitation at Xingshan climate station, which is used by 31 out of 38 subbasins in the Xiangxi Catchment, it becomes clear that there are many situations where a large streamflow peak was observed even though the precipitation event observed on that day or the day before at Xingshan climate station was relatively small. It is very likely that these streamflow peaks were caused by heavy rainfall events occurring in areas of the catchment not covered by any climate stations and therefore SWAT is naturally not able to simulate these streamflow peaks correctly. A similar problem was reported by Inamdar and Naumov (2006) for the Buffalo River Watershed in New York and by Kirsch et al. (2002) for the Rock River Basin in Wisconsin, who concluded that in such cases there is no use in attempting to gain a better fit of observed and simulated peaks. Cao et al. (2006) also stated that the number and location of rain gauges strongly influenced the accuracy of SWAT model predictions in the Motueka Catchment in New Zealand. Xu et al. (2010a) compared the results of two different SWAT model setups for the Xiangxi Catchment, one using climate data measured at Xingshan climate station and the other one using gridded climate data. Their study revealed that the gridded dataset was not able to provide a finer spatial resolution of climate data and resulted in a lower accuracy of streamflow predictions. Therefore, the use of gridded climate data was not considered an option for providing additional data in this study.

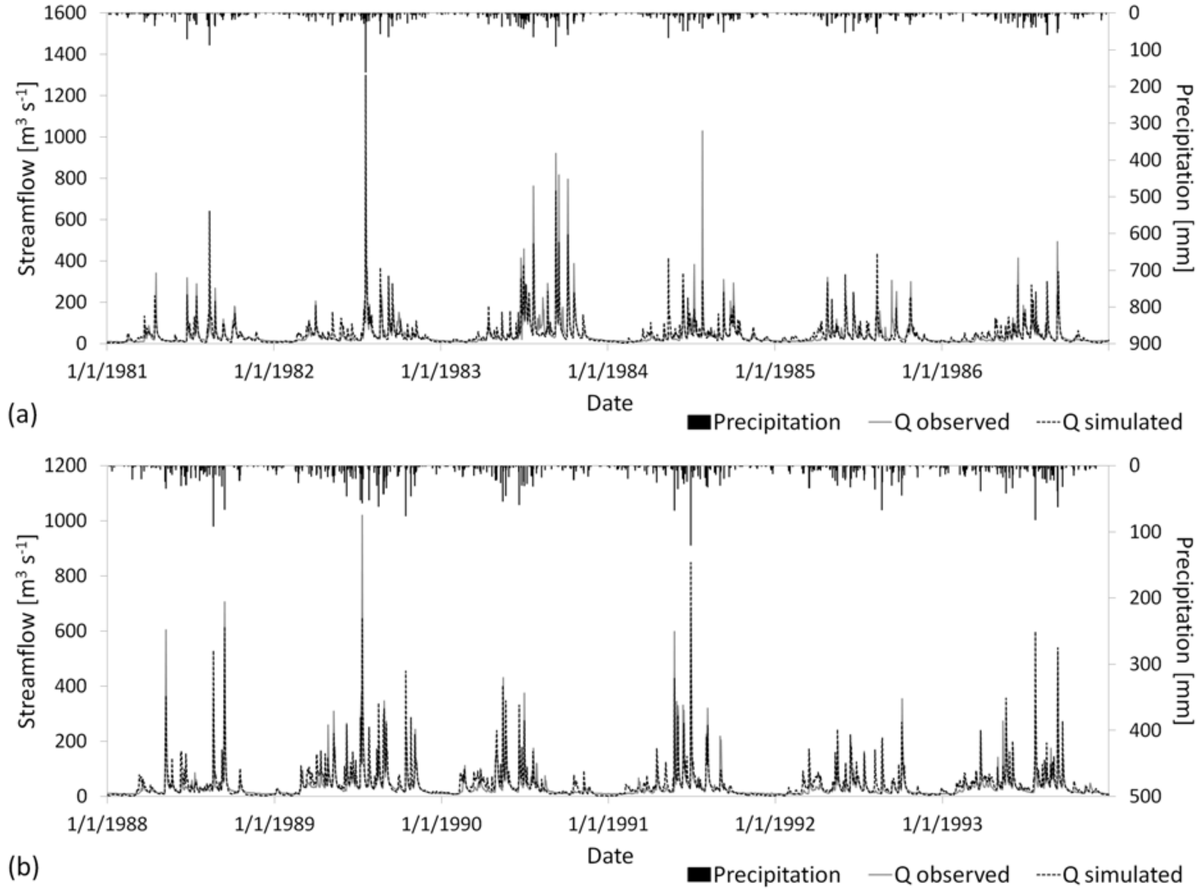

Figure 3.2: Precipitation and hydrographs of observed and simulated daily streamflow at Xingshan station during (a) the calibration period (1981-1986) and (b) the validation period (1988-1993)

In spite of the problems related to the insufficient representation of the spatial variability of rainfall, the model evaluation statistics indicate a generally good model performance for the simulation of streamflow. For the calibration period, the NSE (0.83) and the PBIAS (-5.85) for monthly streamflow indicate a very good model performance according to the general performance ratings proposed by Moriasi et al. (2007) for a monthly time step. For the validation period, the NSE (0.74) indicates a good model performance whereas the PBIAS (-18.30) only indicates a satisfactory fit of simulated and measured monthly streamflow. MAE and RMSE are both slightly lower during the validation period than during the calibration period. As expected, the model evaluation statistics indicate a lower model performance for streamflow on a daily time step. Nevertheless, according to the NSE, which is 0.69 during the calibration period and 0.67 during the validation period, the daily streamflow simulation can still be rated as good (Table 3.2).

Table 3.2: Model evaluation statistics for daily and monthly streamflow during the calibration (1981-1986) and validation (1988-1993) periods

Model evaluation statistic	**Calibration period (1981-1986)**		**Validation period (1988-1993)**	
	Observed	**Simulated**	**Observed**	**Simulated**
Mean, $m^3 s^{-1}$	43.8	46.3	36.9	43.6
Standard deviation, $m^3 s^{-1}$	71.1	64.2	58.8	58.6
Maximum peak, $m^3 s^{-1}$	1030	1299	1020	849
NSE (monthly/daily)	0.83/0.69		0.74/0.67	
R^2 (monthly/daily)	0.84/0.70		0.84/0.71	
PBIAS (monthly/daily)	-5.85/-5.77		-18.3/-18.2	
MAE (monthly/daily)	10.9/17.7		10.3/16.3	
RMSE (monthly/daily)	14.9/39.3		13.8/33.7	

A number of authors like Qi and Grunwald (2005), Kannan et al. (2007b), and Zhang et al. (2011a) highlight the importance of an accurate simulation of all water balance components and runoff pathways. When applying SWAT to a small catchment in the UK, Kannan et al. (2007b) found that even though the simulated and observed hydrographs at the catchment outlet matched well, the internal catchment processes were modeled incorrectly. In the Xiangxi Catchment, ET amounts to 599 mm, which corresponds to 44% of the simulated precipitation, and is assumed to be slightly too low. At the same time, the simulated amount of water yield of 763 mm (55% of precipitation) seems to be required in order to produce the correct amount of streamflow at Xingshan gauging station. Therefore, when increasing ET, a further increase of the precipitation lapse rate would also be necessary to avoid a constant underestimation of streamflow. The adjustment of parameters commonly used to calibrate the amount of ET (e.g. ESCO and EPCO) has shown to be insufficient for increasing ET in the

Xiangxi Catchment. The biomass and leaf area indices of all crops and plants growing in the catchment indicate a reasonable crop growth, but whether the plant parameters in the crop database adequately represent the characteristics of Chinese plant species remains an open question. Some authors like Kannan et al. (2007a) and Earls and Dixon (2008) have achieved better predictions of daily ET when using the Hargreaves method for calculation of ET instead of the Penman-Monteith method. However, in this study, using Hargreaves instead of Penman-Monteith resulted in only marginal increases of simulated ET.

According to the automated digital filter technique used to separate baseflow from surface runoff, baseflow accounted for 50% of the observed and for 46% of the simulated streamflow. This indicates a realistic prediction of the proportions of different runoff components by the model, although Qi and Grunwald (2005) found out in a study conducted in the Sandusky watershed in Ohio that incorrect estimations of water flow in different subbasins often averaged out at the watershed outlet and might thus not be detected when calibrating flow at only one gauge close to the watershed outlet.

3.3.2 Sediment loads

The observed sediment loads are generally characterized by very low values, but there are a few very large peaks associated with streamflow peaks during the monsoon season. Overland erosion is assumed to be the primary contributor of sediment to the rivers, whereas channel erosion is presumed to be of minor importance because of the low availability of erodible fine material in the river channels. Prior to calibration, simulated sediment loads were an order of magnitude higher than observed sediment loads. A spatial analysis of sediment yields revealed that extraordinarily high erosion rates occurred on all agriculturally used HRUs in the catchment. Therefore, to decrease simulated sediment loads, the USLE P factor for agricultural areas was reduced to a value of 0.12. This seems reasonable when considering that most of the agriculturally used slopes in the Xiangxi Catchment are terraced. Also, the USLE C factor for corn and rapeseed were reduced to a value of 0.075. After the USLE P and C factors were adapted, the mean annual sediment yield from agricultural areas was 48 t ha^{-1}, which is the same order of magnitude estimated by other authors for the Three Gorges Region (Lu and Higgitt 2000; Schönbrodt et al. 2010; Shi et al. 2004;). Nevertheless, the calibration of monthly sediment loads at Xingshan gauging station is very problematic, which is illustrated by the sediment graphs in Figure 3.3.

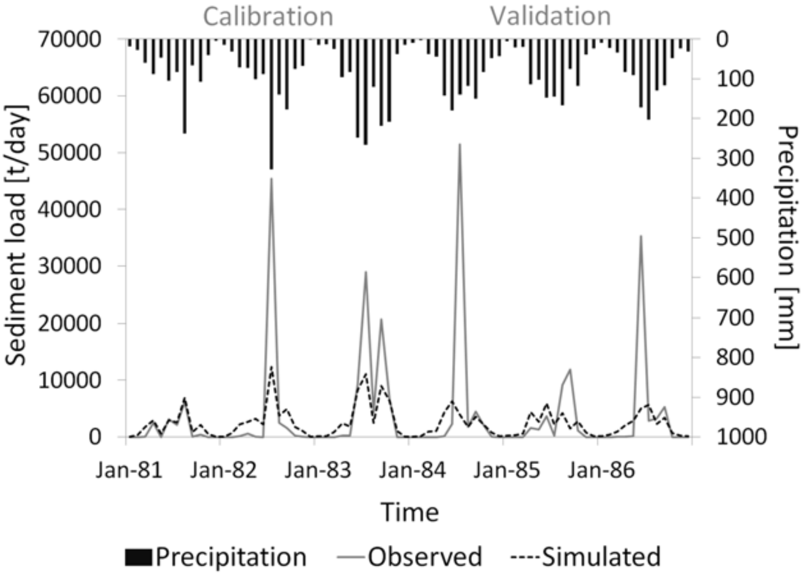

Figure 3.3: Precipitation and sediment graphs of observed and simulated monthly sediment loads at Xingshan station during the calibration (1981-1983) and validation (1984-1986) periods

Table 3.3: Model evaluation statistics for monthly sediment loads during the calibration (1981-1983) and validation (1984-1986) periods

Model evaluation statistic	**Calibration period (1981-1983)**		**Validation period (1984-1986)**	
	Observed	**Simulated**	**Observed**	**Simulated**
Mean, t d^{-1}	3766	2794	3844	2088
Standard deviation, t d^{-1}	9319	3179	10262	1890
Maximum peak, t d^{-1}	45406	12308	51438	6253
NSE	0.47		0.08	
R^2	0.76		0.15	
PBIAS	25.79		45.69	
MAE	2696		3621	
RMSE	6697		9703	

During the first year of calibration, where no large peaks occurred in the observed data, SWAT was able to predict the sediment loads reasonably well. The model performance during the remaining two years of the calibration period and all three years of the validation period is considerably lower as the model is not able to simulate the large peaks in the observed data. The model evaluation statistics indicate an accordingly low model performance especially for the validation period (Table 3.3). A number of reasons might be responsible for this obvious mismatch between observed and simulated data. According to Cao et al. (2006), model errors can be attributed to uncertainties in model parameterization, measurement uncertainties, and errors or oversimplifications in the model structure.

Considerable uncertainty in the simulation of sediment loads in the Xiangxi Catchment is introduced by the observed data used for model calibration and validation. As the exact technique and timing of the sediment sampling is not known (T. Jiang, personal communication, 2010), it is impossible to verify whether sediment loads might be underestimated because short-term events were not captured by the sampling or whether they might be overestimated, because high loads measured during short-term events are extrapolated to whole days. This problem was also mentioned by Benaman et al. (2005). Additionally, measurement errors might have occurred because of the choice of an unrepresentative sampling location or during laboratory analyses.

The high average monthly sediment loads in the observed data in July 1982, July and Sept. 1983, July 1984, Aug. and Sept. 1985 and June 1986 are each caused by only one day with very high loads, but with the exception of 20 July 1982 those high loads are not associated with particularly high amounts of precipitation. Thus another very likely explanation for the disagreement between observed and simulated data is the spatial variability of rainfall already discussed in the above section about streamflow. The simulated sediment loads show a much higher correlation of 0.93 with the observed precipitation than the observed sediment loads (0.44).

The principal aim during sediment calibration was not to match the observed total sediment load, which would have led to a better simulation of sediment in months characterized by one of the extraordinarily high sediment peaks, but also to a considerable overestimation of sediment loads during all remaining months. As there is high uncertainty in the observed data it seems reasonable not to attach to much importance to extreme peaks, which just occur on seven out of 2,192 days and might very well be attributed to measurement errors. Therefore, sediment calibration was rather aiming at matching sediment loads during all months not influenced by one of those seven sediment peaks as closely as possible.

Another factor that might partly explain the large discrepancies between observed and simulated sediment loads in the Xiangxi Catchment is the subdivision of the watershed in subbasins and HRUs. A number of authors have investigated the effects of watershed subdivision and concluded that the number and size of subbasins can cause large variations in SWAT sediment predictions. Arabi et al. (2006) observed a strong increase of sediment yields, when they decreased the size of subbasins in two watersheds in Indiana. Studies by Bingner et al. (1997) in the Goodwin Creek Watershed in Mississippi, by FitzHugh and Mackay (2000) in the Pheasant Branch Watershed in Wisconsin, by Jha et al. (2004) in four watersheds in Iowa, and by Migliaccio and Chaubey (2008) in the Illinois River Watershed in Arkansas also revealed that the predicted sediment yield was very sensitive to the subbasin delineation. Jha et al. (2004) recommend including a sensitivity analysis with varying subbasin delineations in watershed modeling studies, which has not been done in this study yet.

Furthermore, sediment predictions may be influenced by the resolution of the DEM, the soil map and the land use map. The resolution of the DEM affects the subbasin delineation and the calculation of topographic parameters and has been shown to impact sediment yields in studies conducted by Cotter et al. (2003) in the Moores Creek Watershed in Arkansas, Chaplot et al. (2005) in the Lower Walnut Creek watershed in Iowa and Di Luzio et al. (2005) in the Goodwin Creek watershed in Mississippi. In the Lower Walnut Creek Watershed, finer soil information also improved SWAT sediment predictions (Chaplot et al. 2005), whereas the scale of the soil map did not influence model results in the Goodwin Creek watershed (Di Luzio et al. 2005). Both the DEM and the soil map used in this study for the Xiangxi Catchment are rather coarse. In addition, soil parameters were not available for all soil types occurring in the Xiangxi Catchment, so that for some parameters the same values had to be used for different soil types, which caused a further oversimplification of soil information and may have reduced the accuracy of sediment simulation results due to a worse estimation of soil-related processes. In their study in the Goodwin Creek Watershed, Di Luzio et al. (2005) also found a relationship between the spatial resolution of the land use map used and the sediment yields. They state that finer land use and soil maps can increase the number of HRUs and thus allow for the definition of more precise and diversified management patterns. This might also be of importance in the Xiangxi Catchment as it is characterized by small scale agriculture with fields that are mostly much smaller than the grid size of the land use map. Moreover, because of a lack of information about crop rotations, tillage operations, and the amounts and timing of fertilizer applications, management schemes had to be kept very simple in this study, which introduced a further oversimplification of land use data.

Further uncertainties in the model parameterization may be attributed to the databases in SWAT, which were mostly developed to reflect North American conditions and which will have to be adapted to Chinese conditions as stated by Shen et al. (2011). Ongley et al. (2010) question the transferability of SWAT databases to Chinese conditions as well, especially in agriculturally dominated watersheds, as only few Chinese crops are represented in the crop database and as it is difficult to adequately consider the impacts of terraced agriculturally used slopes and rice paddies on runoff processes.

An additional problem for the calibration of sediment loads might be inherent in the model structure. SWAT uses the MUSLE to estimate soil losses from each HRU within a subbasin, which are then summed up to calculate the subbasin's total soil loss. The MUSLE was developed using data from 18 watersheds in the southern USA and proved to explain most of the variation observed in sediment loads (Williams 1975). Thus it accounts for the sediment delivery ratios in those 18 watersheds. However, if a watershed of interest is characterized by a different sediment transport capacity, the estimated sediment delivery ratio may be incorrect. Because there are apparent differences between the catchment characteristics of the Xiangxi Catchment and watersheds in the southern USA, this can be assumed to impact the sediment loads at Xingshan gauging station, even though the specific interactions of soil loss, sediment delivery and sediment loads have not been evaluated for the Xiangxi Catchment yet.

In spite of the difficulties encountered during sediment calibration the results of this study provide a sufficient basis for further environmental research in the Xiangxi Catchment. Due to the construction of the Three Gorges Dam land use in the Xiangxi Catchment and in the Three Gorges Region in general has already changed substantially in the past 20 years and will continue to do so in the future. Soil erosion and sediment inputs to rivers are expected to increase because of this land use change. Measurements in the Xiangxi Catchment have revealed a strong relationship between sediment and phosphorus concentrations, which suggests that most of the phosphorus is transported attached to the sediment. The combination of increasing inputs of sediment and phosphorus and reduced flow velocities and prolonged residence times of water in the reservoir is assumed to induce a higher risk of eutrophication. However, the specific impacts of the Three Gorges Dam construction and reservoir impoundment on water quality have not been quantified yet. Xu et al. (2011a) point out that currently there is no suitable analytical tool for quantifying the environmental effects of the land use change due to resettlements and the relocation of agricultural areas in the Three Gorges Region. This study provides the first step towards filling this gap in knowledge by setting up the SWAT model for the Xiangxi Catchment and highlighting further research needs. The results of this study reveal a lack of empirical data to parameterize and verify the model, which was also described by Ongley et al. (2010). They also indicate the need to revise knowledge of basic processes and their mathematical representation in order to better account for the specific characteristics of Chinese catchments. The application of hydrological models like SWAT to Chinese catchments in order to improve their capability to represent Chinese conditions is an important prerequisite for simulating land use and management scenarios and identifying suitable strategies for non-point source pollution control, especially in the highly dynamic ecosystems of the Three Gorges Region.

3.4 Conclusions

The aim of this study was to calibrate and validate SWAT for streamflow and sediment yield predictions the Xiangxi Catchment in China in order to assess the general applicability of the model to data scarce catchments in the Three Gorges Region and to provide a sound basis for land use scenario simulations.

The results for daily streamflow are generally very good, even though ET in the Xiangxi Catchment is slightly underestimated by the model. Also, most streamflow peaks are either under- or overestimated, which is assumed to be due to an inadequate representation of spatial rainfall variability.

The simulation results for sediment loads reveal a strong need for further research analyzing the impact of the information regarding the spatial variability of rainfall, soils, and land use as well as the delineation of subbasins on predicted sediment loads for SWAT applications in China. Furthermore, plant parameters and management practices represented in the SWAT databases need to be enhanced in order to better account for Chinese conditions. A few of these issues will be investigated in this study before evaluating different land use and management scenarios in the Xiangxi Catchment using SWAT.

3.5 Acknowledgements

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Chapter 4

The impact of land use change in the Xiangxi Catchment (China) on water balance and sediment transport

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Abstract

The construction of the Three Gorges Dam on the Yangtze River led to the resettlement of more than one million people including the relocation of agriculturally used areas from the valley bottoms to steep, formerly forested slopes. This is expected to induce an increase in surface runoff, soil erosion and sediment inputs to rivers and can seriously impair the quality of surface waters in the Three Gorges Region. The aim of this study was to simulate past and future land use changes in the Xiangxi Catchment with the eco-hydrological model SWAT (Soil and Water Assessment Tool) (Version SWAT2009, Revision 530) in order to quantify impacts on hydrology and sediment transport.

The Xiangxi Catchment covers an area of 3,200 km^2 and is located approximately 40 km upstream of the Three Gorges Dam. In spite of the resettlement of people and the relocation of agricultural areas, according to the land use maps used in this study the forested area in the watershed has increased by 3.6% between 1987 and 2007. Also, large areas of cropland were replaced with orange orchards, which are assumed to provide better soil protection than crops. Accordingly, simulation results demonstrate that surface runoff, soil erosion, streamflow and sediment loads have decreased by 5.9, 47.7, 0.7 and 41.9%, respectively.

Scenario simulations indicate that any additional increase of forested area in the Xiangxi Catchment would further reduce surface runoff and sediment yields, but at the same time would increase the pressure on remaining cropland. Positive effects of afforestation could be outweighed by the negative effects of a further intensification of land use in other parts of

the watershed. Economic growth and increasing population pressure are likely to lead to a demand for additional farmlands. Simulation results have shown that when only areas with slopes <25° are brought into cultivation surface runoff and sediment yields could increase considerably.

The results of this study indicate a strong need for sustainable development and management of land in the Xiangxi Catchment to find a balance between the demands of environmental protection and agricultural production.

4.1 Introduction

Land use is rated as one of the most important factors influencing water quantity and quality in watersheds. Not only are hydrological processes such as evapotranspiration, infiltration, surface runoff and groundwater flow altered substantially by land use changes (Bultot et al. 1990; Fohrer et al. 2001; Lin et al. 2007; Sahin and Hall 1996; Tong and Chen 2002), but also soil erosion and the transport of sediment to water bodies. The evaluation of the impacts of land use change on water quantity and quality is fundamental to the development of sustainable land use alternatives (Lenhart et al. 2003; Lin et al. 2007) and is an integral component of river basin and water resources management (Eckhardt et al. 2003; Huisman et al. 2004).

One of the most ecologically sensitive areas in China is the Three Gorges Region (TGR) (Tian et al. 2010), which comprises 19 counties along the Yangtze River between the cities of Yichang and Chongqing (Bu et al. 2008). It covers a total area of 62,640 km^2 (Wang et al. 2010). The TGR is strongly influenced by the Three Gorges Project (Shen et al. 2010a), one of the largest dam projects in the world (Tian et al. 2010). The construction of the Three Gorges Dam started in 1993 and was completed in 2009 (Zhang et al. 2009). At the maximum water level of 175 m.a.s.l. the reservoir has a total storage volume of 39.3 billion m^3 (Ming et al. 2009) and stretches over a distance of more than 600 km.

The TGR is heavily influenced by soil erosion and non-point source pollution of surface waters with sediments and nutrients (Lu and Higgitt 2001; Shen et al. 2010a, 2010b; Tian et al. 2010). An estimated area of 33,000 km^2 in the TGR is affected by moderate or severe soil erosion (Ng et al. 2008), which is mostly attributed to the use of steep slopes for agricultural production (Lu and Higgitt 2001). Because of the mountainous terrain, poor soils, a population exceeding the land carrying capacity and a lack of income alternatives, people in the TGR are forced to adopt environmentally unfriendly and unsustainable cultivation practices (Jim and Yang 2006). Before the construction of the dam, the annual soil loss in the TGR and the annual sediment delivery to the Yangtze River were estimated to be 157 million and 41 million tons, respectively (Shi et al. 1992). Since dam construction started, land use in the TGR has been influenced by a number of factors increasing the pressure on the land area (Jim and Yang 2006) and thus leading to an intensification of land use, which is presumed to increase surface runoff, erosion and sediment inputs to surface waters.

According to official numbers, more than 1 million people had to be resettled because of the impoundment of the Three Gorges Reservoir (Xu et al. 2011a). Many of them were resettled within their original counties and moved upslope to steep, formerly forested areas, abandoning prime agricultural land in the valleys and leaving it to inundation. Zhang et al. (2009) state that approximately 240 km^2 of agricultural land were flooded by the Three Gorges Reservoir, while Lu and Higgitt (2001) estimate the submerged agricultural land to be 316 km^2. The soils on the steep slopes are mostly of poor structure and characterized by a low organic matter content (Shi et al. 2004) and are much less productive than the soils in the river valleys. Shi et al. (1992) estimated a need of five times the previous agricultural area in order to produce the same amount of harvest on sloping cropland (Lu and Higgitt 2001). Also, the Three Gorges Project has boosted the regional economy considerably and the region has experienced a strong growth in population, both increasing the demand for agricultural products on the one hand and built-up area on the other hand (Zhang et al. 2009).

Due to the high erosion rates, the TGR is one of the main target areas of the Sloping Land Conversion Program (SLCP), which was launched in 1999 as a consequence of the devastating Yangtze River floods in the summer of 1998 (Bennett 2008). Through compensation and subsidy payments, farmers were encouraged to convert agricultural land on slopes >25° to forest or grassland (Xu et al. 2006; McVicar et al. 2007; Ouyang et al. 2008; Wang et al. 2007). While SLCP has been shown to be an effective means of reducing soil erosion on the afforested areas, it also decreased the land area available for agriculture and put further pressure on the remaining areas of cropland (Jim and Yang 2006).

As a result of erosion and sediment transport, the nutrient-rich topsoil is removed from the agricultural areas, leading to an irreversible degradation of soils and to undesired off-site effects in water bodies. The sediment reduces the life span of the Three Gorges Reservoir due to siltation (Higgitt and Lu 2001; Wang et al. 2010) and carries large amounts of nutrients to the water bodies (Ouyang et al. 2010). Sediment deposited in the reservoir can potentially desorb considerable amounts of phosphorus (Wang et al. 2009), which has shown to be the limiting nutrient for algae growth in the Three Gorges Reservoir. At the same time, the flow velocity in the reservoir is reported to be at least five times lower than before the impoundment (Tullos 2009), which prolongs the residence time of the water. In combination, these factors are assumed to increase the risk of eutrophication substantially (Dai et al. 2010). Especially in the backwater areas of the Yangtze River tributaries, algae blooms have been observed more frequently since the construction of the dam (Dai et al. 2010; Li et al. 2008; Xu et al. 2011b; Ye et al. 2007; Zeng et al. 2006; Zhang et al. 2010a; Zhong et al. 2005).

Land use planning in China has to take into account not only the demands for food, raw materials and urban expansion, but also the requirements of environmental protection (Yin et al. 2010). In the TGR, soil loss and sediment delivery to surface waters have to be reduced by implementing soil conservation measures (Lu and Higgitt 2001). Field experiments are often too expensive, labor-intensive and do not offer the possibility to evaluate the impacts of changes in land use and management before these have actually occurred. Therefore, models are needed to predict the effects of land use changes on water resources. Due to the ability to represent the spatial variability of land surface characteristics and hydrological processes, physically based, distributed models are of particular importance for the prediction of land use change effects (Klöcking and Haberlandt 2002; Legesse et al. 2003). The use of eco-hydrological models provides an insight into the consequences of changes in policies or other land use determinants (Fohrer et al. 2002, 2005; Van Rompaey et al. 2001; Verburg and Veldkamp 2001) and can contribute to decision-making in the fields of land use planning and integrated watershed management (Leh et al. 2011).

The aim of this study was to simulate past and possible future land use changes in the Xiangxi Catchment in the TGR using the eco-hydrological model SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998) in order to quantify their impacts on hydrology and sediment transport. Results are expected to provide useful information for a sustainable development of land use and water resources management. This study was designed to address the following research questions: (1) How did the land use changes that occurred between the first preparations for the construction of the Three Gorges Dam and its completion affect the hydrology and the sediment transport in the Xiangxi Catchment and (2) what would be the impacts of possible future changes in land use?

4.2 Materials and methods

4.2.1 Study area

The Xiangxi Catchment covers an area of 3,200 km^2 and is located in Hubei Province in Central China (Figure 4.1). It extends over Xingshan County as well as parts of Shennongjia and Zigui Counties. The watershed is characterized by large differences in elevation, ranging from 3,078 m.a.s.l. near the source of the Xiangxi in the Shennongjia Mountains to 62 m.a.s.l. at the mouth of the Xiangxi, which is located approximately 40 km upstream of the Three Gorges Dam. With a mean gradient of 24° and a maximum gradient of 76°, slopes in the watershed are very steep. The Xiangxi is 94 km long and has two large tributaries, the Gufu and the Gaolan Rivers (Figure 4.1).

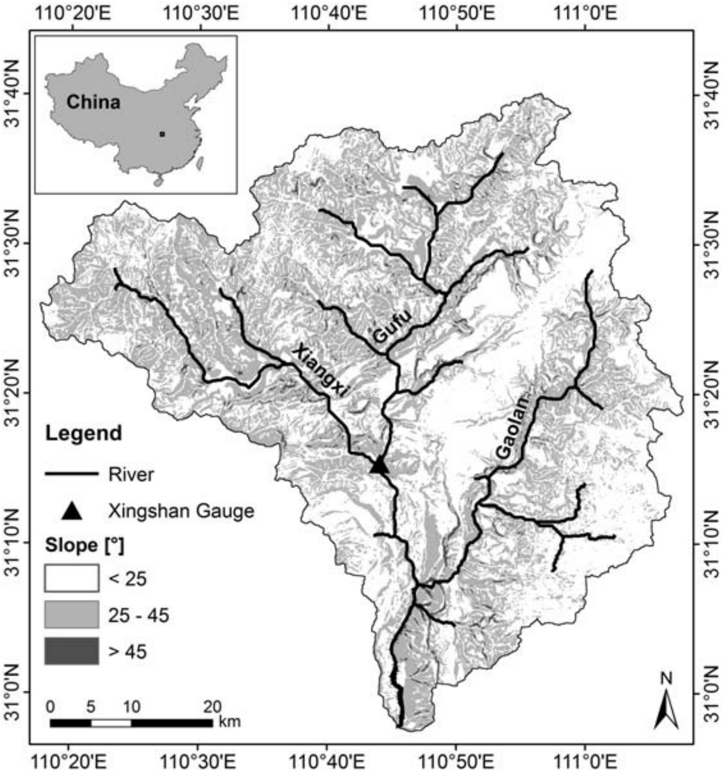

Figure 4.1: Slope classes and river network of the Xiangxi Catchment and its location in China

Mean annual streamflow (1970-2005) at Xingshan Gauge amounts to 36.75 m^3 s^{-1}. Mean annual temperature and precipitation (1961-1990) at Xingshan are 16.9°C and 1,000 mm, respectively. The climate in the TGR is strongly influenced by the subtropical summer monsoon with a rainy season from April to September and a dry season from October to

March. Accordingly, runoff and soil erosion mostly occur in summer (Ng et al. 2008; Shen et al. 2010b). Temperature and precipitation are additionally influenced by the mountainous topography and vary considerably with altitude (He et al. 2003). The dominant soil types in the watershed are Limestone soils and Yellow-brown soils (Genetic Soil Classification of China).

4.2.2 Land use change between 1987 and 2007

The Xiangxi Catchment is strongly influenced by the Three Gorges Project. The reservoir expands approximately 30 km into the Xiangxi River and flooded an area of 9,700 ha, including cropland, forest, and residential areas (Guo et al. 2003). Because of rural resettlements and the construction of the new district town Xingshan, land use in the Xiangxi Catchment has changed considerably in the last 25 years. The development of land use and its driving forces was analyzed by Seeber et al. (2010, 2012) on the basis of three land use maps derived from Landsat TM images from the years 1987, 1999 and 2007. A total of seven land use classes were identified from the satellite images: forest, cropland, orange orchards, water, built-up land, bare ground and grassland. Table 4.1 lists the percentages of area in the Xiangxi Catchment covered by the three dominant land use types in 1987, 1999 and 2007 and the percental change between 1987 and 1999, 1999 and 2007, and 1987 and 2007.

Table 4.1: Area in the Xiangxi Catchment covered by the three dominant land use types forest, cropland and orange orchard and change between the land use maps from 1987, 1999 and 2007

Land use type	**Area [km^2]**			**Change [%]**		
	1987	**1999**	**2007**	**1987-1999**	**1999-2007**	**1987-2007**
Forest	2664	2756	2760	+3.44	+0.16	+3.61
Cropland	421	332	304	-21.06	-8.76	-27.97
Orchard	55	44	72	-20.42	+63.38	+30.01

Forest is the dominating land use type in the Xiangxi Catchment, covering 83.7% of the watershed area in 1987 and increasing to 87% in 2007. Cropland and orange orchards are located primarily along the rivers and roads, especially in the southern part of the watershed. Cropland has decreased from 13.3 to 9.6% between 1987 and 2007; the proportion of orange orchards has increased from 1.7 to 2.3%. The increase in forest occurred mostly between 1987 and 1999 because of the abandonment of cropland in remote and inaccessible areas of the watershed. Between 1999 and 2007 forest increased only marginally whereas considerable areas of cropland were converted to orange orchards (Seeber et al. 2012). The remaining land use types water, built-up land, bare ground and grassland are of relatively minor importance (Seeber et al. 2010). On higher elevations, tea is planted as a cash crop (He et al. 2003), but could not be distinguished from forest by Seeber et al. (2010) (C. Seeber, personal communication, 2009). The Xiangxi Catchment is distinctive of the eastern part of the TGR, which is generally dominated by forest with only small portions of cropland (Xu et al. 2011a).

4.2.3 Land use scenarios

Scenarios are not meant to predict exactly what is going to happen in the future, but rather describe possible future trends in order to estimate the consequences of different circumstances and identify the most appropriate responses to changing conditions (Zhu et al. 2011). A total of three land use scenarios depicting different hypothetical situations were developed based on the trends of land use change observed in the past. Seeber et al. (2010, 2012) identified elevation, slope and distance to main roads and to the Three Gorges Reservoir as the most important driving factors of land use change in the Xiangxi Catchment. Ye et al. (2009) found high correlations of land use with elevation and slopes in this watershed. The three land use scenarios used in this study were developed as a function of slope, elevation and distance to rivers. The roads are accounted for indirectly because they mostly run parallel to the main rivers. All three scenarios were developed based on the land use map from 2007.

- Scenario 1 (S1) estimates the impacts of a continuation of SLCP. The forested area in the watershed is assumed to further increase because of a conversion of all remaining croplands on slopes >25° to forest.
- Scenario 2 (S2) is accounting for an increasing demand for agriculturally used areas in the Xiangxi Catchment, but assumes an effective enforcement of SLCP. A conversion of forest to cropland takes place in a 1 km wide buffer zone along the Xiangxi, Gufu and Gaolan Rivers, where in elevations >750 m.a.s.l. forest on slopes <25° is converted to cropland. In elevations <750 m.a.s.l. forest on slopes <45° is converted to orange orchards. Cropland on slopes >25° is converted to forest in the entire watershed.

- Scenario 3 (S3) is a rather extreme scenario presuming a strong intensification of land use in the Xiangxi Catchment. In addition to the land use changes in the direct vicinity of the river that were already applied in S2, selected forested areas on slopes <25° are converted to cropland in the remaining parts of the watershed. While on elevations <1,000 m.a.s.l. this affects all, on elevations between 1,000 and 2,000 m it only affects half of the forested areas on slopes <25°. On elevations >2,000 m.a.s.l. land use is not changed.

4.2.4 The SWAT model

SWAT (Arnold et al. 1998) is an eco-hydrological model, which was developed to predict the impact of land use and land management practices on water, sediment, and agricultural chemical yields in large watersheds. It is a continuous time model designed for simulating long periods of time (Arnold et al. 1998; Arnold and Fohrer 2005; Neitsch et al. 2011). SWAT has been used for the assessment of land use and management impacts on water quantity and quality in many studies worldwide, including an increasing number of studies in China (Guo et al. 2008; He et al. 2008; Ouyang et al. 2008; Wang et al. 2008).

In SWAT, the watershed is divided into subbasins, which are then further subdivided into hydrological response units (HRUs). These are lumped areas within a subbasin with a unique combination of slope, soil type, and land use. Simulation of the hydrologic cycle is separated into a land phase and a water phase (Neitsch et al. 2011). The simulation of the land phase is based on the water balance equation, which is calculated separately for each HRU. Runoff generated in the HRUs is summed up to calculate the amount of water reaching the main channel in each subbasin (Neitsch et al. 2011). The water phase of the hydrologic cycle describes the routing of runoff in the river channel, using the variable storage coefficient method by Williams (1969).

Sediment yield is estimated for each HRU using the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975). Sediment routing in the channel is controlled by two processes, degradation and deposition, with deposition occurring when the upland sediment load is larger than the transport capacity of the channel and degradation occurring when it is smaller. The transport capacity of a channel segment is calculated as a function of the peak channel velocity (Arnold et al. 1995).

SWAT allows for detailed management schemes to be defined for each HRU, including time of planting and harvesting, time and amount of fertilizer and pesticides applications, irrigation, and grazing. Crop growth is controlled by an extensive crop database, which provides plant parameters for a large number of plants and land cover types. A detailed description of the model is given by Neitsch et al. (2011).

4.2.5 SWAT model application in the Xiangxi Catchment

The basic calibration and validation of SWAT was done using the land use map from 1987. Streamflow records measured from 1981 to 1986 at Xingshan Gauge were used for calibration of the model. The time period from 1988 to 1993 was used for model validation. For sediment, the model was calibrated for the years 1981 to 1983 and validated during the years 1984 to 1986, because the available time series of observed sediment loads ends in 1986. A detailed description of the calibration and validation of SWAT for the Xiangxi Catchment is given by Bieger et al. (2012). However, due to a change from revision 477 to revision 530 of the current version of the model (SWAT2009), a minor recalibration of the model was necessary, resulting in a slightly better model performance, which was evaluated using the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), the coefficient of determination (R^2) and the percent bias (PBIAS). In order to be able to evaluate the impacts of land use changes isolated from the influence of other factors, e.g. the construction of two small reservoirs on Gufu River, the six models set up with the land use maps from 1987, 1999 and 2007 and the hypothetical land use maps S1, S2 and S3 were run for the same period of time from 1981 to 1993. The former three are referred to as S1987, S1999 and S2007 hereafter.

4.3 Results

4.3.1 Land use change between 1987 and 2007

In spite of the low amount of data available for the Xiangxi Catchment, the basic calibration of SWAT for the Xiangxi Catchment using the land use map from 1987 resulted in a satisfactory agreement between observed and simulated values, which is confirmed by the model evaluation criteria (Table 4.2). Model performance during the validation period is slightly lower for streamflow and considerably lower for the sediment loads. According to the performance ratings proposed by Moriasi et al. (2007), model results for monthly and daily streamflow and monthly sediment loads for S1987 can be rated as very good, good and satisfactory, respectively. Figure 4.2 shows the yearly averages of streamflow and sediment loads at Xingshan Gauge for all years of both the calibration and the validation periods.

Table 4.2: Model evaluation statistics for daily and monthly streamflow and monthly sediment load simulations for S1987

Model evaluation statistic	**Streamflow (daily/monthly)**		**Sediment load (monthly)**	
	Calibration	**Validation**	**Calibration**	**Validation**
NSE	0.69/0.87	0.68/0.84	0.52	0.07
R^2	0.71/0.91	0.69/0.84	0.77	0.13
PBIAS	9.12/9.20	3.74/3.67	-3.78	27.21

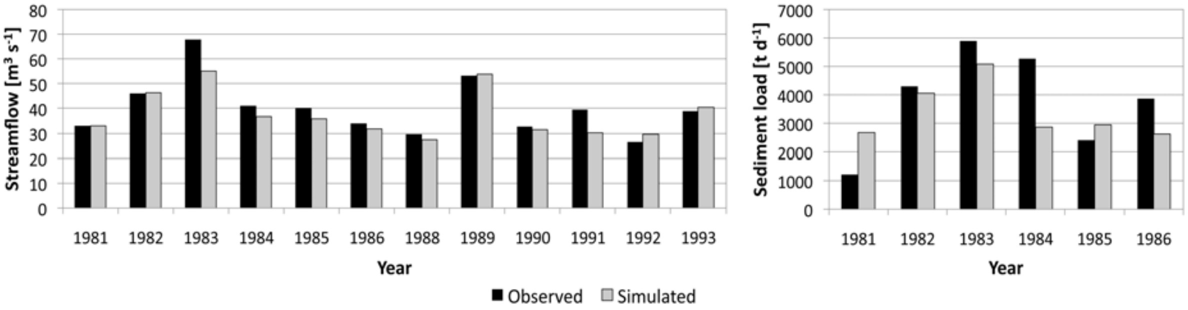

Figure 4.2: Observed and simulated yearly streamflow and sediment loads for S1987

In S1987, the watershed average annual evapotranspiration and water yield amounted to 836.4 and 621.8 mm and thus to 57 and 43% of the average annual precipitation, respectively. The land use change between S1987 and S2007 had minor impacts on the average annual evapotranspiration (ET) and water yield (Figure 4.3). From S1987 to S1999, ET increased by 3.5 mm (0.4%) to an average of 839.9 mm a^{-1}. From S1999 to S2007 it increased by an additional 0.7 mm to an average of 840.6 mm a^{-1}. In contrast, the water yield decreased by 4.2 mm (0.7%) to an average of 617.6 mm a^{-1} in S1999. From S1999 to S2007 it was reduced by an additional 1.6 mm to an average of 616.0 mm a^{-1}. The proportions of the flow components surface runoff (Q_{surf}), lateral flow (Q_{lat}) and groundwater flow (Q_{gw}) changed considerably between S1987 and S1999 and marginally between S1999 and S2007 (Figure 4.3). From S1987 to S1999, Q_{surf} decreased by 11.1 mm (5.4%) from 250.7 to 237.2 mm, while Q_{gw} and Q_{lat} increased by 13.4 mm (4.1%) from 151.6 to 157.8 mm and by 10.1 mm (1.5%) from 223.1 to 226.4 mm, respectively. From S1999 to S2007, Q_{surf} decreased by an additional 1.4 mm, whereas Q_{lat} increased by 0.1 mm. Q_{gw} decreased by 0.4 mm.

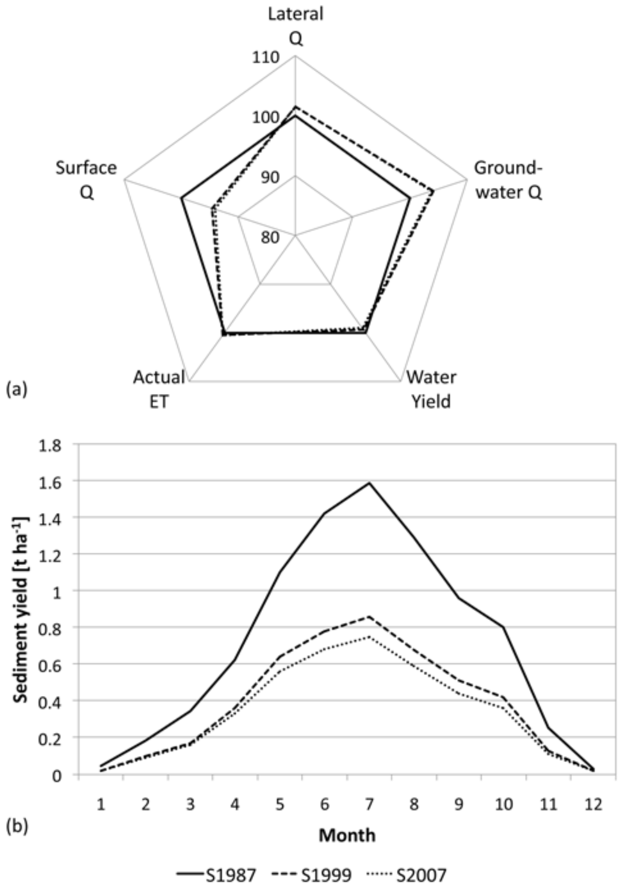

Figure 4.3: Percent changes of modeled water balance and flow components from S1987 (100%) to S1999 and S2007 (a) and modeled average monthly sediment yield in S1987, S1999 and S2007 (b)

The average annual sediment yield amounted to 6.84 t ha^{-1} in 1987. It decreased to 4.69 t ha^{-1} in S1999 and to 4.12 t ha^{-1} in S2007. Figure 4.3 shows that the highest sediment yield occurs during summer, especially in July, when precipitation is high, whereas the sediment yield is very low in winter.

The modeled changes in the water balance induced very small changes in the average annual streamflow at Xingshan Gauge, which decreased from 37.42 m^3 s^{-1} in 1987 to 37.19 m^3 s^{-1} in S1999 and finally to 37.16 m^3 s^{-1} in S2007 (Table 4.3). This is mostly due to a decrease of streamflow during the summer season (April to October). During the dry season in winter (November to March) streamflow did not change.

The impacts of the changes in land use between S1987 and S2007 on the average annual sediment load were much more obvious than those on the average annual streamflow at

Xingshan Gauge (Table 4.3). Between S1987 and S1999, the average annual sediment load at the gauge decreased from 2562 to 1571 t d^{-1}. The decrease from S1999 to S2007 was less pronounced, but still sediment loads decreased by an additional 81 t d^{-1} to an amount of 1490 t d^{-1}. Considerable reductions in sediment load were calculated both for the dry winter and for the wet summer season.

Table 4.3: Changes in modeled average annual and seasonal streamflow and sediment loads at Xingshan Gauge from S1987 to S1999 and S2007 (S=Summer, W=Winter)

Model setup	**S1987**			**S1999**			**S2007**		
	Year	**S**	**W**	**Year**	**S**	**W**	**Year**	**S**	**W**
Streamflow [m^3 s^{-1}]	37.42	52.88	21.89	37.19	52.42	21.89	37.16	52.36	21.89
Change in streamflow [%]	---	---	---	-0.61	-0.86	+/-0	-0.69	-0.97	+/-0
Sediment [t d^{-1}]	2562	4190	927	1571	2606	531	1490	2471	504
Change in sediment [%]	---	---	---	-38.69	-37.80	-42.70	-41.85	-41.02	-45.63

4.3.2 Land use scenarios

The land use scenarios had the expected effects on the water balance. The changes in land use in S1 led to a 2.2% increase of forest in the watershed compared to 2007, which is equivalent to an area of 60 km^2. Cropland decreased by the same acreage, which is equivalent to a reduction of 19.7% of this land use type (Table 4.4). Accordingly, with regard to the watershed hydrology the development already observed between S1987 and S2007 continued. Compared to S2007, the average ET for the entire Xiangxi Catchment was 0.2% higher in S1, whereas the average water yield was 0.4% lower. In S1, ET and water yield amounted to 842.6 and 613.9 mm a^{-1} on watershed average, respectively. Q_{surf} decreased by 3.5% compared to S2007 and amounted to 227.6 mm in S1, whereas Q_{lat} and Q_{gw} increased by 2.2 and 0.9% to values of 231.4 and 158.7 mm, respectively (Figure 4.4).

Table 4.4: Area in the Xiangxi Catchment covered by the three dominant land use types forest, cropland and orange orchards and change compared to S2007

Land use type	**Scenario 1 (S1)**		**Scenario 2 (S2)**		**Scenario 3 (S3)**	
	km^2	**Change [%]**	**km^2**	**Change [%]**	**km^2**	**Change [%]**
Forest	2820	+2.17	2482	-10.09	1809	-34.48
Cropland	244	-19.72	358	+17.86	1109	+265.32
Orchard	72	+/-0	296	+313.71	218	+204.51

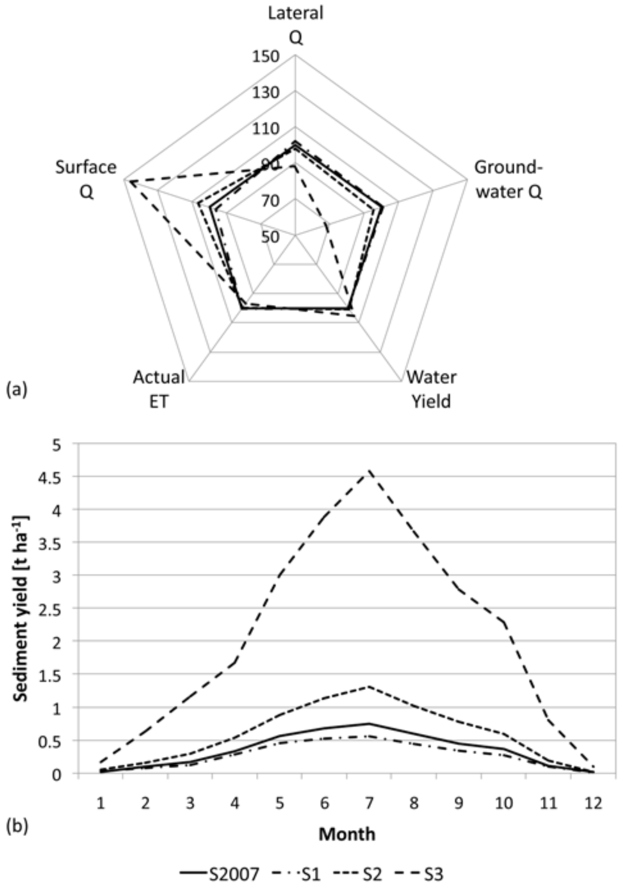

Figure 4.4: Percent changes of modeled water balance and flow components from S2007 (100%) to S1, S2 and S3 (a) and modeled average monthly sediment yield in S2007, S1, S2 and S3 (b)

The changes in land use in S2 resulted in an increase of cropland and orange orchards by 17.9% and 313.7%, respectively, and in a decrease of forest by 10.1% (Table 4.4). In spite of the conversion of all cropland on slopes >25°, the intensification of land use in the direct vicinity of the rivers in this scenario led to a 0.5% decrease of ET and a 0.7% increase in water yield compared to S2007. Accordingly, in S2 ET and water yield on watershed average amount to 836.8 and 620.2 mm, respectively. Q_{surf} increased by 6% to an amount of 251.9 mm, whereas Q_{lat} and Q_{gw} were reduced by 2.0 and 4.6% to amounts of 221.9 and 150.1 mm, respectively (Figure 4.4).

The changes in land use in S3 led to a 34.5% decrease of forest compared to S2007 and in considerable gains in cropland and orange orchards of 265.3 and 204.5%, respectively (Table 4.4). S3 is an extreme scenario, which resulted in more obvious effects on the water balance and flow components than both the past land use changes and scenarios S1 and S2. Continuing the development already observed in S2, ET decreased further in S3, while the water yield increased. Compared to S2007, ET decreased by 3.4% to an amount of 811.9 mm. Simultaneously, the water yield increased by 5.2% to an amount of 647.9 mm. The impacts of the land use changes in S3 were even more pronounced with regard to the flow components Q_{surf}, Q_{lat}, and Q_{gw}. While Q_{surf} increased by 46.1% to an amount of 344.7 mm, Q_{gw} and Q_{lat} were reduced by 11.7 and 31.8%, respectively. Accordingly, Q_{lat} and Q_{gw} amounted to 200.0 and 107.3 mm in S3 (Figure 4.4).

Amounting to 3.14 t ha^{-1}, the average annual sediment yield was lower in S1 than in 2007. In accordance with Q_{surf}, the average annual sediment yield was higher in S2 (6.89 t ha^{-1}) and especially in S3 (24.67 t ha^{-1}) than in S2007. The monthly variability did not change in the scenarios. Again, the highest sediment yield occurred in July, while the lowest sediment yield was estimated for the time period from November to March (Figure 4.4).

The effects of S1 and S2 on the average annual streamflow were relatively small (Table 4.5). The land use changes in S1 led to a reduction of streamflow by 0.4% to an amount of 37.0 $m^3 s^{-1}$, which is mostly due to a decrease of streamflow during the wet summer months. The land use changes in S2 induced an increase of average annual streamflow of 0.6% to an amount of 37.4 $m^3 s^{-1}$, even though streamflow only increased during the summer whereas it decreased slightly during winter. Similar, but more pronounced changes were estimated by SWAT for S3. The changes in this scenario led to a 4% increase in average annual streamflow compared to S2007.

Table 4.5: Changes in modeled average annual and seasonal streamflow and sediment loads at Xingshan Gauge from S2007 to S1, S2 and S3 (S=Summer, W=Winter)

Model setup	**S1**			**S2**			**S3**		
	Year	**S**	**W**	**Year**	**S**	**W**	**Year**	**S**	**W**
Streamflow [$m^3 s^{-1}$]	37.04	52.12	21.89	37.37	52.82	21.85	38.80	55.84	21.86
Change in streamflow [%]	-0.4	-0.5	+/-0	+0.6	+0.9	-0.2	+4.4	+6.6	-1.0
Sediment [$t d^{-1}$]	1132	1893	368	2525	4181	862	9570	15447	3669
Change in sediment [%]	-24.0	-23.4	-27.0	+69.5	+69.2	+70.9	+542	+525	+627

S1 continued the development already observed from S1987 to S2007 with regard to the average annual sediment loads at Xingshan Gauge as well, which were reduced by 24.0% to an amount of 1,132 t ha^{-1}. The strongest decrease of the total amount of sediment loads occurred during summer, when streamflow and sediment loads are generally high, but the percental reduction was higher in winter than in summer. In contrast to S1, the average annual sediment loads increased in S2 and especially in S3, as expected because of the increase in agriculturally used areas in the Xiangxi Catchment. In S2, sediment loads increased by 69.5% to an amount of 2,525 t d^{-1}. S3 induced a strong increase in average annual sediment loads by 542% to an amount of 9,570 t d^{-1}. Again, percental changes were higher during winter, whereas the changes in the total amounts were higher during summer (Table 4.5).

4.3.3 Spatial variability of sediment yields

The average annual sediment yields vary considerably between the 38 subbasins of the Xiangxi Catchment (Figure 4.5). In 1987, the highest sediment yields were calculated for the southern part of the watershed, especially for the subbasins along the lower reaches of Xiangxi and Gaolan Rivers, and for the subbasins along the upper reaches of Xiangxi River, which are located in the Shennongjia Mountains. The lowest sediment yields were estimated for the subbasins along the upper reaches of Gufu River.

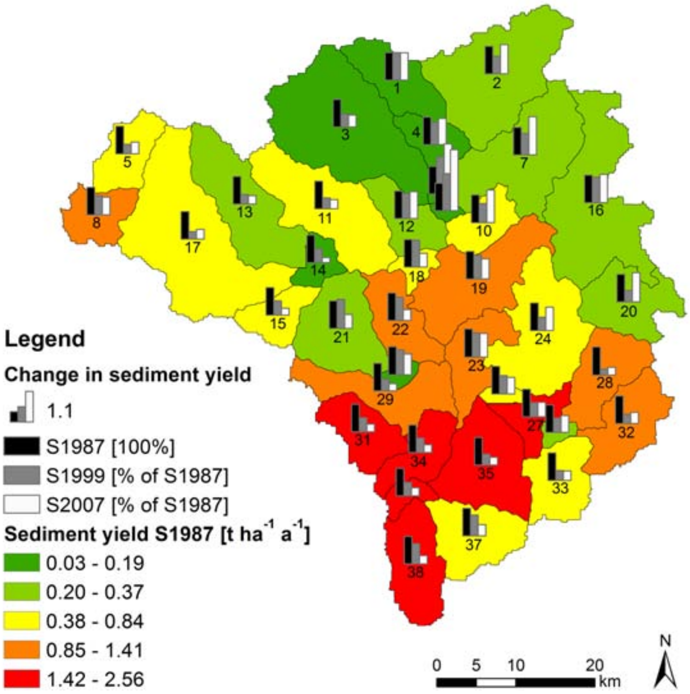

Figure 4.5: Average annual sediment yield in S1987 and change in sediment yield from S1987 to S1999 and S2007 per subbasin

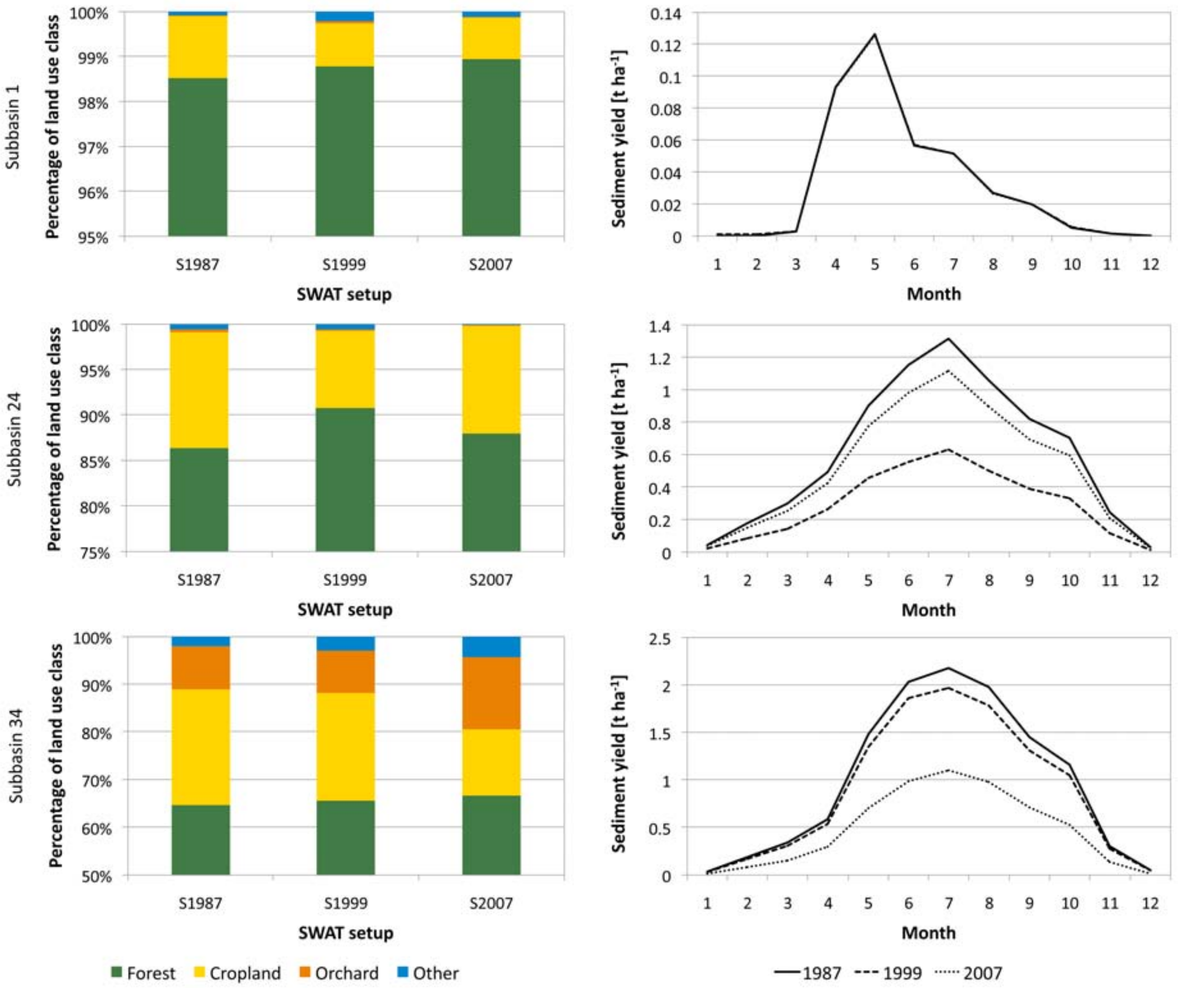

Figure 4.6: Land use allocation and average monthly sediment yields in three selected subbasins (1, 24 and 34) in S1987, S1999 and S2007

There is a distinct variability in the changes in sediment yield from S1987 to S1999 and S2007. While in most subbasins the sediment yields decreased considerably from S1987 to S1999 and continued to do so from S1999 to S2007, there are some subbasins, which demonstrated a contrasting behavior. Mostly in the upper reaches of Gufu River, the sediment yields in some subbasins increased or remained almost constant between S1987 and S2007 or they decreased from S1987 to S1999, but increased again between S1999 and S2007, sometimes even to a higher level than in S1987.

Figure 4.6 shows the change in average monthly sediment yields and the allocation of land use types in three selected subbasins, which are characterized by different changes in land use and accordingly also by different effects on the sediment yield between S1987 and S2007. Subbasin 1 is almost completely forested. The proportion of cropland was reduced from 1.4%

in S1987 to less than 1% in S1999 and S2007, but even before this the cropland area was too small to exert a considerable influence on the sediment yield. Therefore, the sediment yield did not change noticeably in the observed time period. Subbasin 24 is characterized by a much higher proportion of cropland than subbasin 1. In S1987, 13% of subbasin 24 were covered by cropland. Between S1987 and S1999, the cropland area decreased to 8.5%, but then increased again to 12% in S2007. This led to a decrease of sediment yield from S1987 to S1999 and a subsequent increase from S1999 to S2007. In subbasin 34, the agriculturally used area is higher than in subbasin 24, but is divided into cropland and orange orchards. In 1987, cropland and orange orchards covered 24 and 9% of the subbasin, respectively. Between S1987 and S1999, cropland decreased to 22%, while the area covered by orange orchards remained almost constant. From S1999 to S2007, cropland was reduced for the benefit of orange orchards, which increased to 15% of the subbasin. Forest increased slightly from S1978 to S1999 and also from S1999 to S2007. This led to a moderate decrease of sediment yield between S1987 and S1999 and to a much more pronounced decrease from S1999 to S2007, which can mostly be attributed to the replacement of cropland with orange orchards.

The changes in average annual sediment yields per subbasin in the three scenarios S1, S2, and S3 vary spatially (Figure 4.7). In S1, the average annual sediment yields are reduced to between 30 and almost 100% of the amounts estimated for S2007. Differences in the magnitude of the reduction of average annual sediment yields can be attributed to the varying intensity of land use change in the subbasins. The influence of the nature and intensity of land use change on the changes in sediment yields per subbasin are even more clearly recognizable in the results for S2. The average annual sediment yields increased in most of the subbasins due to the strong increase in agriculturally used areas along the rivers. However, there are some subbasins where the average annual sediment yields decreased because the increase in forest on slopes >25° outweighed the increase in agriculturally used areas. Therefore, the average annual sediment yields in those subbasins are lower in S2 than in S2007. In S3, sediment yields increased in all subbasins, which can clearly be attributed to the strong increase in agriculturally used areas on slopes <25% throughout the entire watershed. The percental changes are highest in the remotely located subbasins which were characterized by an above average proportion of forest cover in S2007 and where the percental increase of agriculturally used areas was therefore higher than in subbasins that were more intensely used in S2007.

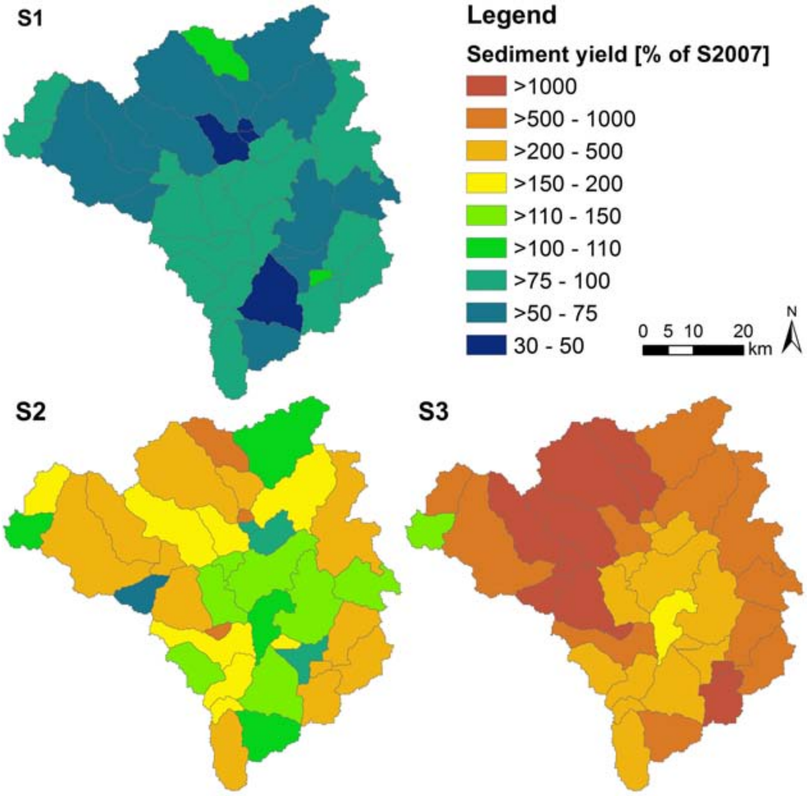

Figure 4.7: Changes in average annual sediment yield per subbasin for the three land use scenarios S1, S2 and S3 compared to the average annual sediment yield in S2007

4.4 Discussion

The model results for monthly and daily streamflow and monthly sediment loads for S1987 are considered a sufficient basis for the simulation of land use scenarios. Nevertheless, it is important to consider the uncertainties in the model results, which can originate from the input data, the model parameters and the model structure (Breuer et al. 2006). In this study, the most important source of uncertainty is the climate data, which is only available at a very coarse spatial resolution. As there are only three climate stations located within or very close to the watershed, the spatial variability of precipitation is not captured sufficiently, which leads to an under- or overestimation of most streamflow peaks. Uncertainties in the model results are discussed in detail by Bieger et al. (2012). According to Hessel et al. (2003), when doing scenario analyses, all scenarios for a watershed are subject to the same input data uncertainty, so it can be assumed that relative differences in scenario results can in fact be attributed to the applied scenario changes.

Effects of the past land use changes in the Xiangxi Catchment on the water balance components and the streamflow were relatively small, which is consistent with the findings of other land use change studies. Many authors found that because of compensating effects in complex watersheds with a variety of land use types, impacts of land use changes on hydrology are relatively small at large scales, while they are much more pronounced at smaller scales (Cao et al. 2009; Costa et al. 2003; Fohrer et al. 2001).

Simulation results indicate that soil loss and sediment loads have decreased between S1987 and S2007 in accordance with the increase in forest areas and the decrease of surface runoff. Thus, according to model results the feared increase in erosion due to land use change induced by the construction of the Three Gorges Dam has not occurred yet. However, the results obtained by SWAT depend heavily on the quality of the land use classification by Seeber et al. (2010). A major problem is posed by the fact that tea plantations could not be distinguished from forest and therefore do not occur on the land use maps even though considerable areas of tea plantations can be found in the northern part of the Xiangxi Catchment. This leads to an overestimation of the forested area in the watershed. As tea is assumed to provide less soil cover than forest, this presumably leads to an underestimation of sediment yields from the affected areas.

Even though sediment yields are estimated by SWAT to have decreased in the past, under the modified conditions in the Three Gorges Reservoir with reduced flow velocities and prolonged residence times of water, the current sediment and nutrient inputs still appear to be critical, as indicated by an increasing occurrence of algae blooms especially in the backwater areas of Yangtze River tributaries including the Xiangxi River (Ye et al. 2006, 2007, 2009). Sediment yields calculated by SWAT for the Xiangxi Catchment were in a similar order of magnitude as those estimated by Shen et al. (2010b) (0.2 - 3.8 t ha^{-1} a^{-1}) and Ng et al. (2008) (2.2 - 9.4 t ha^{-1} a^{-1}) for small watersheds in Zigui County. On basin average, the sediment yield in the Xiangxi Catchment in S2007 was estimated to be 4.1 t ha^{-1} a^{-1}, and thus slightly lower than the soil loss tolerance value of 5 t ha^{-1} a^{-1} that was suggested by the Ministry of Water Resources of China (1997) (Shi et al. 2004; Wang et al. 2010). However, the mean annual soil loss from cropland and orange orchards in the Xiangxi Catchment in S2007 was estimated to be 23.6 and 5.1 t ha^{-1}, respectively. Even though the average soil loss from orange orchards was only marginally higher than the soil loss tolerance value, almost 30% of the HRUs where orange trees are growing were characterized by much higher average annual soil losses of up to 36.3 t ha^{-1}.

Similar soil loss rates were reported by Wang et al. (2010) for two experimental plots on citrus orchards in Zigui County. Average annual soil losses from cropland calculated in this study were even higher and ranged from 1.9 to 108.3 t ha^{-1} with only about 10% of the HRUs exhibiting values below the soil loss tolerance value. For economic reasons, the Rural Water Conservancy and Soil Conservation Bureau of the Changjiang River Water Resources Commission (RWCSCB 1998) increased the soil loss tolerance value to 10 t ha^{-1} (Shi et al. 2004). According to the simulation results for S2007, even this less stringent limit is exceeded by 71 and 14% of the croplands and orange orchards, respectively.

Against the background of the already high eutrophication risk in the Three Gorges Reservoir and the high soil loss rates from croplands and partly also from orange orchards, a sustainable development of land use and land management in the TGR is of high importance. As it is very difficult to predict which of the many factors influencing the land use change in the region are going to be the decisive ones in the future, it is advisable to estimate the effects of different possible future land use patterns. Therefore, a total of three land use scenarios were developed in this study.

Simulation results indicate that a further increase in forested areas, as assumed in scenario S1, would continue the trends observed between S1987 and S2007. With regard to safeguarding the water resources in the TGR, this scenario represents the most sustainable option and meets the requirements specified by SLCP. However, the long-term success of SLCP still remains difficult to predict. Depending on whether cropland is converted to grassland or to forest, farmers participating in the program receive payments for two to eight years, but their livelihood is not improved considerably (Long et al. 2006). Therefore, a number of authors assume that many farmers will be forced to convert the new grasslands or forests back to cropland once the subsidy payments have stopped (Jim and Yang 2006; Long et al. 2006). They criticize the lack of efforts to create long-term, non-agricultural sources of income, optimize the local agricultural structure and improve cultivation techniques. Additionally, the feasibility of a further increase of forest in the Xiangxi Catchment is generally questionable. Hubacek and Sun (2001) estimated that an annual increase in the productivity of Chinese cropland of 1.28% would be necessary to accommodate the increasing demand that is due to economic and population growth alone. Further compensation is required for the loss of cropland to other land uses such as forest or urban areas. A further increase of forest in the Xiangxi Catchment could considerably increase the pressure on the remaining agricultural areas and also complicate local resettlement (Jim and Yang 2006). It is questionable whether the benefits of a further increase in the forested area will be large enough to outweigh the negative impacts of a further intensification of the remaining croplands.

Scenarios S2 and S3 assume an increase in orange orchards and cropland to a different degree, with the priority set on orchards or cropland depending on elevation and slope. While the land use changes happening in S2 lead to relatively moderate increases in sediment yields, which are still lower than those simulated for S1987, the land use pattern in S3 results in extraordinarily high sediment yields. Ghaffari et al. (2010) have found that there exist certain thresholds for different processes in hydrological systems, above which the response rapidly becomes more intense. Whether such a threshold exists regarding the sediment yields in the Xiangxi Catchment would have to be investigated by setting up further land use scenarios that describe different intermediate stages between S2 and S3.

Different studies in the TGR have obtained contradictory results regarding the soil conservation effect provided by the vegetation cover of orange orchards and cropland. While Shen et al. (2010b) concluded from their study in the Zhangjiachong Watershed that crops provide better soil cover and protection than orange orchards, Meng et al. (2001) state the opposite for the Wangjiaqiao Watershed. In this study, it was assumed that orange orchards provide a better soil protection than cropland, which is consistent with the SWAT default parameterization of oranges and the crops rapeseed and corn, which were chosen to represent the diverse pattern of crops in the Xiangxi Catchment in the model. The relatively large area of orange orchards in S2 explains why the sediment yields in this scenario are still lower than those calculated for the baseline scenario even though the forested area is lower.

It is questionable how realistic scenarios S2 and S3 are with regard to the expansion of orange orchards, when the necessary infrastructure and facilities for processing the oranges are not provided. Also, it is important to consider that the degree of soil cover provided by orange orchards is highly dependent on the growth stage of the trees. A mature stand of orange trees is characterized by a dense canopy, which intercepts large amounts of rainfall and reduces the rainfall velocity and erosivity. A newly planted orange orchard in contrast is usually characterized by small trees growing scattered on bare ground and therefore providing hardly any soil protection at all. It was not possible to consider different growth stages of orange orchards in this study, because the land use classification by Seeber et al. (2010) did not allow for a distinction of dense and sparse orchards.

An intensification of land use due to an increasing demand for agricultural products is assumed to especially affect the areas in the immediate vicinity of the rivers and the Three Gorges Reservoir. For reasons of accessibility, intensively used areas in the Xiangxi Catchment are preferentially located close to roads, which due to the mountainous terrain often run directly adjacent to the rivers. Additionally, many of the resettled families in the area desired to stay in very close proximity to their former home and merely moved from the valley bottoms to adjacent slopes (Xu et al. 2011a). It is important to consider that a close proximity of cultivated land to surface waters can considerably increase the potential to impact water quality because the shorter the distance between field and water body the higher the sediment delivery ratios usually are. However, the analysis of subbasin averages of sediment yield presented in this study does not provide information in sufficient spatial detail, as the average values are strongly impacted by the large proportions of forest in most of the subbasins. An analysis of sediment yields on HRU level could provide more detailed information and help to identify critical source areas of sediment and therefore to locate areas in the watershed where there is a strong need to establish more sustainable land use types or adopt more sustainable land management practices.

4.5 Conclusions

The aim of this study was to assess the impacts of past and future land use change on water balance, streamflow and sediment transport in the Xiangxi Catchment in the TGR in Central China, which is currently subject to a large scale land use change induced by the construction of the Three Gorges Dam on the Yangtze River.

The results of this study indicate the strong need for sustainable development and management of land use in the Xiangxi Catchment. They demonstrate that in spite of a reduction of agriculturally used areas in the Xiangxi Catchment in the past, sediment inputs to rivers are still high. Cultivated sloping land is identified as the major contributor to soil loss and sediment yields. Because of nutrients attached to the soil particles, the sediment inputs entail a high risk of eutrophication, especially since the formation of backwater areas in the Yangtze River tributaries has reduced the flow velocities and accordingly increased the residence times considerably. A sustainable watershed management is crucial for ecological preservation and for safeguarding the future usability of water resources in the TGR. The simulation of land use scenarios has been used in this study to estimate the effects of possible future land use patterns on the water balance and the sediment transport in the Xiangxi Catchment and to point out possible conflicts between the interests of environment and local population.

The scenarios do not include alterations of crop rotations or tillage practices or the implementation of soil conservation practices. This is an important topic, which should be addressed by further research in the Xiangxi Catchment and the entire TGR. However, further studies in the Xiangxi Catchment rely heavily on the improvement of input data in order to reduce uncertainties in the model parameterization. This is a crucial requirement not only for the simulation of changes in land management practices, but also for the estimation of the effects of changes in model parameters other than those strictly related to land use, especially changes in soil hydraulic properties.

For the Xiangxi Catchment, especially data on crop rotations, tillage, and soil properties have to be refined. Also, a classification of land use on a finer spatial scale would reduce the uncertainty resulting from the aggregation of plant characteristics over the spatial subunits of the model. This can facilitate the distinction of dense and sparse orchards, which will allow for a more realistic estimation of sediment yields from orange orchards in the watershed. Additionally, land use maps used for future studies in the Xiangxi Catchment should include tea plantations.

With an enhanced database SWAT simulations in the Xiangxi Catchment can contribute to an improved representation of the characteristics of Chinese watersheds in the model, e.g. with regard to soil erosion processes and sediment delivery ratios, and also to a more sustainable watershed management in the TGR. This study is a first step towards a better understanding of the interactions between land use change and hydrological processes in an ecologically very sensitive area which is expected to be subject to ongoing changes in the decades ahead.

4.6 Acknowledgements

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Chapter 5

Detailed spatial analysis of the plausibility of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China

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Abstract

The Three Gorges Region in China is characterized by severe soil erosion, which leads to a degradation of soils and receiving surface waters and indicates a need for sustainable watershed management including the adoption of Best Management Practices to reduce soil erosion. For an effective targeting of Best Management Practices the identification of Critical Source Areas within watersheds is crucial. Watershed models like SWAT (Soil and Water Assessment Tool) are valuable tools that allow for the identification of Critical Source Areas in large watersheds and for the assessment of the effectiveness of Best Management Practices without time-consuming and costly field experiments.

In this study, SWAT was applied to the Xiangxi Catchment in the Three Gorges Region. Surface runoff and sediment yields were analyzed at the most detailed spatial level available in the model, the Hydrologic Response Unit (HRU) level. This allows for a more precise targeting of Best Management Practices than analysis at subbasin level. Additionally, it provides the opportunity to validate simulated amounts of surface runoff and sediment yield by checking the plausibility of their spatial variation within the watershed based on expert knowledge.

Results of this study indicate that satisfactory model performance at the gauge does not guarantee plausible results at HRU level. Both surface runoff and sediment yields display reasonable variation with land use and soil types, but not with slope. However, a plausible variation of processes as a function of slope is considered very important in mountainous

watersheds like the Xiangxi Catchment. With regard to surface runoff, inconsistencies can mostly be attributed to minor simplifications in SWAT algorithms computing surface runoff and to a strong indirect impact of lateral flow on surface runoff. Plausibility of surface runoff was increased in this study by modifying and recalibrating selected SWAT algorithms and parameters. However, the effects of these modifications on sediment yield are marginal. This can be explained by the non-linear relationship between sediment yield and HRU area in the Modified Universal Soil Loss Equation used by SWAT for calculating sediment yield, which allows the HRU area to exert a stronger influence on estimated sediment yields than the remaining factors of the equation.

This study demonstrates that a detailed analysis of model output at HRU level during model calibration is highly recommendable. This is of particular importance when SWAT is used as a tool to identify Critical Source Areas for targeting Best Management Practices. Also, detailed analysis of the plausibility of SWAT output at HRU level can help to validate model simulations in watersheds where there is little observed data available for extensive model calibration and validation.

5.1 Introduction

The Three Gorges Region (TGR) in the upper reaches of Yangtze River in China is characterized by very high erosion rates. Shi et al. (1992) estimated the annual soil loss in the region at 157 million tons and the sediment delivery to the Yangtze at 41 million tons. According to Ng et al. (2008) an area of 33,000 km^2 in the TGR is affected by moderate or severe soil erosion, which can mostly be attributed to the use of steep slopes for agricultural production (Lu and Higgitt 2001). Mountainous terrain, poor soils, a population exceeding the land carrying capacity and a lack of income alternatives has forced the local population to adopt environmentally unfriendly and unsustainable cultivation practices (Jim and Yang, 2006).

The construction of the Three Gorges Dam on Yangtze River induced the resettlement of more than one million people and the relocation of agriculturally used areas from the valley bottoms to steep, formerly forested slopes (Cai et al. 2005; Lu and Higgitt 2000; Meng et al. 2001). Due to their poor structure and low organic matter content, the soils on steep slopes are less productive than the soils in the flat river valleys (Shi et al. 2004). This results in a need of five times the area to produce the same amount of harvest (Shi et al. 1992). The increasing use of steep slopes for agricultural production is expected to further increase soil erosion and sediment inputs to surface waters in the future.

Erosion leads to the loss of the nutrient-rich topsoil and thus to a degradation of soils. Also, the soil transports nutrients and agricultural chemicals and therefore impacts the water quality of receiving water bodies (Lenhart et al. 2005). The control of soil erosion and sediment inputs to surface waters is an important task in the context of environmental planning and natural resources management. The ability to quantify and predict soil loss and sediment yields is required for the identification of Critical Source Areas (CSA) and the development of suitable strategies to manage agricultural pollution. Best Management Practices (BMP) have proven to be an efficient means of reducing soil erosion and surface water pollution with sediment and agricultural chemicals (Arabi et al. 2007; Lam et al. 2012). However, the effectiveness of BMPs depends largely on their placement within the watershed (Giri et al. 2012). For erosion control, it is important to target those parts of a watershed where the highest soil loss and the largest sediment delivery ratios occur. Watershed models can provide estimates of the impact of BMPs at the watershed scale (Arabi et al. 2008).

A number of models have been developed for the assessment of soil erosion and sediment transport related processes. The simplest and most widely used erosion model is the empirical Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978). Also, soil erosion and sediment transport are considered by many hydrological and water quality models. The eco-hydrological model SWAT (Soil and Water Assessment Tool; Arnold et al. 1998) uses the Modified Universal Soil Loss Equation (MUSLE; Williams 1975), a derivative of the USLE, to quantify sediment yields. In the MUSLE, the rainfall energy factor used in the USLE is replaced with a runoff factor (Neitsch et al. 2011).

SWAT is a semi-distributed model, which divides the watershed into subbasins. These are further subdivided into Hydrologic Response Units (HRU), i.e. lumped areas within a subbasin with a unique combination of land use, soil type and slope. Accordingly, SWAT allows for the distinction of sediment yields from different land uses, soils and slope classes. However, in most studies SWAT output is aggregated on watershed or subbasin level (e.g. Behera and Panda 2006; Jha et al. 2010; Kepner et al. 2004; Lam et al. 2012; Mishra et al. 2007; Mukundan et al. 2010; Ouyang et al. 2010; Rocha et al. 2012; Saghafian et al. 2012; Tripathi et al. 2003). Behera and Panda (2006) and Tripathi et al. (2003) identified critical subbasins for targeting BMPs based on thresholds for average annual sediment yields and nutrient losses. In the Xiangxi Catchment, the proportion of forested areas, where surface runoff and sediment yields are low, is very high in most subbasins. As a result, subbasin average amounts of surface runoff and sediment yield are very low, even though small areas within a subbasin may be characterized by high emissions and thus contribute considerably to non-point source pollution.

The analysis of SWAT output at HRU level allows for a more precise identification of CSAs and a more efficient targeting of BMPs. However, only very few studies include an HRU-based analysis of SWAT output (e.g. Busteed et al. 2009; Fohrer et al. 2005; Haverkamp et al. 2005; Panagopoulos et al. 2011; White et al. 2009). Additionally, the analysis of model output at HRU level provides the opportunity to identify strengths and limitations of the algorithms used to estimate surface runoff and sediment yields in SWAT and to identify crucial inconsistencies in the model parameterization. HRU-based analysis should be part of model calibration in any watershed model application, but can be particularly helpful in data-scarce watersheds where little observed data is available for the calibration and validation of a hydrological model. Even though it may not always be possible to verify the exact amounts of surface runoff and sediment yield simulated by SWAT, uncertainties in model results can be minimized by ensuring plausible spatial patterns of runoff and sediment yields within a watershed.

The main objective of this study was to analyze SWAT (Version SWAT2009, Revision 530) output at HRU level to evaluate the plausibility of the simulated surface runoff and sediment yield in the Xiangxi Catchment in the TGR and improve it where necessary and possible. Because of the mountainous terrain of the watershed, the focus was laid on the dependence of surface runoff and sediment yield on slope, which has been shown to exhibit some inconsistencies. A plausible simulation of variations in simulated processes with slope is of central importance in the context of model applications to mountainous watersheds. Therefore, this study aimed at answering the following research questions:

1. Is the spatial variation of simulated surface runoff and sediment yield consistent with the parameterization of land use, soil and slope?
2. What are the main reasons for inconsistencies in the dependence of simulated surface runoff and sediment yield on slope?
3. How can the dependence of surface runoff and sediment yield on slope be improved in the model?

5.2 Materials and methods

5.2.1 The eco-hydrological model SWAT

The model SWAT (Arnold et al. 1998) was developed for the evaluation of the impacts of land use and management practices on hydrology and water quality in large complex watersheds (Neitsch et al. 2011). A graphical user interface, ArcSWAT (Olivera et al. 2006), is available and a convenient tool for setting up SWAT, modifying input parameters and running the model.

SWAT is a semi-distributed model and divides a watershed into subbasins, which are further subdivided into Hydrologic Response Units (HRU). Each HRU is characterized by a unique combination of land use type, soil type, and slope class. For the calculation of all hydrological and matter transport processes, the model distinguishes between a land phase and a water phase. Processes happening in the land phase are calculated based on the water balance equation and include precipitation, evapotranspiration (ET), surface runoff, infiltration, soil storage, lateral flow, groundwater recharge, and groundwater flow. Runoff as well as sediment and agricultural chemical yields from all HRUs within a subbasin are summed and enter the main reach of the subbasin. In the water phase, water, sediments, and agricultural chemicals are routed through the channel network to the outlet of the watershed. The algorithms calculating surface runoff, lateral flow and sediment yield from the HRUs play a crucial role in this study and are therefore the most important equations are explained in the following chapters based on Neitsch et al. (2011).

5.2.1.1 Calculation of surface runoff

In SWAT, surface runoff is predicted using the SCS curve number (SCS-CN) method, which was developed by the Soil Conservation Service (SCS 1972). It calculates surface runoff according to the equation:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{5.1}$$

where Q_{surf} is the surface runoff [mm], R_{day} is the rainfall for the day [mm], I_a is the initial abstractions including surface storage, interception and infiltration prior to runoff [mm], which is commonly approximated as 0.2S, and S is a retention parameter. The maximum value the retention parameter can achieve on any day is calculated with the equation:

$$S_{max}=25.4\left(\frac{1000}{CN_1}-10\right) \tag{5.2}$$

where CN_1 is the curve number assigned to the HRU, which depends on the permeability of the soil, land use, and antecedent soil moisture.

The permeability of a soil is expressed by assigning the soil to one of four Soil Hydrologic Groups (NRCS Soil Survey Staff 1996). The Soil Hydrologic Groups A, B, C and D have a high, moderate, slow and very slow infiltration rate when thoroughly wetted, respectively. The antecedent soil moisture can be described by either one of three conditions: I (wilting point), II (average moisture) and III (field capacity). Typically, the curve number (CN) is given for moisture condition II and are appropriate for a 5% (2.9°) slope. The ArcSWAT interface provides the option to adjust CN to a different slope using the equation:

$$CN_{2s}=\frac{(CN_3-CN_2)}{3}\cdot[1-2\cdot\exp(-13.86\cdot slp)]+CN_2 \tag{5.3}$$

where CN_{2s} is the moisture condition II curve number adjusted for a given slope, CN_3 is the moisture condition III curve number for the default 5% (2.9°) slope, CN_2 is the moisture condition II curve number for the default 5% (2.9°) slope and *slp* is the average slope of the HRU. The equations used for the conversion of CN2 to CN1 and CN3 values are given by Neitsch et al. (2011).

The retention parameter is updated daily as a function of either the soil profile water content or the plant ET. When the retention parameter varies with the soil water content it is updated according to the following equation:

$$S=S_{max}\cdot\left(1-\frac{SW}{SW+\exp(w_1-w_2\cdot SW)}\right) \tag{5.4}$$

where S is the retention parameter for a given day [mm], S_{max} is the maximum retention of an HRU [mm], SW is the water content of the soil profile excluding the amount of water held in the soil at wilting point [mm] and w_1 and w_2 are shape coefficients, which are determined based on the maximum retention of the HRU, the amount of water in the soil profile at field capacity and the amount of water in the soil profile when completely saturated. For the equations used to calculate w_1 and w_2 please refer to Neitsch et al. (2011).

When the retention parameter is updated as a function of plant evapotranspiration it is calculated as:

$$S = S_{prev} + ET \cdot \exp\left(\frac{-cncoef \cdot S_{prev}}{S_{max}} \right) - R_{day} + Q_{surf} \qquad (5.5)$$

where S is the retention parameter for a given day [mm], S_{prev} is the retention parameter on the previous day [mm], ET is the potential evapotranspiration for the day, S_{max} is the maximum parameter, *cncoef* is a weighting coefficient, R_{day} is the rainfall for the day [mm] and Q_{surf} is the surface runoff [mm].

5.2.1.2 Calculation of lateral flow

In SWAT, lateral flow occurs whenever the water content of the soil exceeds its water content at field capacity. Lateral flow is calculated using the equation:

$$Q_{lat} = 0.024 \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}} \right) \qquad (5.6)$$

where Q_{lat} is the lateral flow [mm day^{-1}], $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hillslope per unit area [mm], K_{sat} is the saturated hydraulic conductivity of the soil [mm h^{-1}], *slp* is the increase in elevation per unit distance, ϕ_d is the drainable porosity of the soil [mm mm^{-1}] and L_{hill} is the hillslope length [m]. Multiplying K_{sat} with *slp* gives the net discharge at the hillslope outlet, while the remaining factors describe the saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness.

The net discharge at the hillslope outlet is actually calculated by the equation:

$$v_{lat} = K_{sat} \cdot \sin(\alpha_{hill}) \qquad (5.7)$$

where K_{sat} is the saturated hydraulic conductivity of the soil [mm h^{-1}] and α_{hill} is the slope of the hillslope segment [°]. However, the slope is input to SWAT as the increase in elevation per unit distance which is equivalent to the tangent of α_{hill}. To simplify the formula, the tangent of α_{hill} is assumed to equal the sine of α_{hill}, so slp can be used instead of the sine of α_{hill} in Equation 6.

5.2.1.3 Calculation of sediment yield

Sediment yield is calculated in SWAT using the Modified Universal Soil Loss Equation (Williams 1975):

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (5.8)$$

where *sed* is the sediment yield on a given day [metric tons], Q_{surf} is the surface runoff [mm], q_{peak} is the peak runoff rate [m^3/s], $area_{hru}$ is the area of the HRU [ha], K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and *CFRG* is the coarse fragment factor. The USLE factors are described in detail by Wischmeier and Smith (1978) and Neitsch et al. (2011).

The peak runoff rate is calculated as:

$$q_{peak} = \frac{C \cdot i \cdot Area}{3.6} \qquad (5.9)$$

where q_{peak} is the peak runoff rate [m^3 s^{-1}], *C* is the runoff coefficient, *i* is the rainfall intensity [mm hr^{-1}], *Area* is the HRU area [km^2] and 3.6 is a unit conversion factor. The calculation of the runoff coefficient and the rainfall intensity is explained by Neitsch et al. (2011).

5.2.2 The Xiangxi Catchment

The Xiangxi Catchment is located in the western part of Hubei Province in Central China (Figure 5.1). The Xiangxi is the first large tributary of Yangtze River upstream of the Three Gorges Dam. It is 94 km long and has two major tributaries, the Gufu and the Gaolan Rivers.

The Xiangxi Catchment comprises an area of 3,200 km^2. With elevations ranging from 62 m.a.s.l. at the confluence with Yangtze River to 3,078 m.a.s.l. near the source of the Xiangxi in the Shennongjia Mountains, it is characterized by large differences in elevation and steep slopes. The mean and the maximum slope gradient in the watershed are 24 and 76°, respectively.

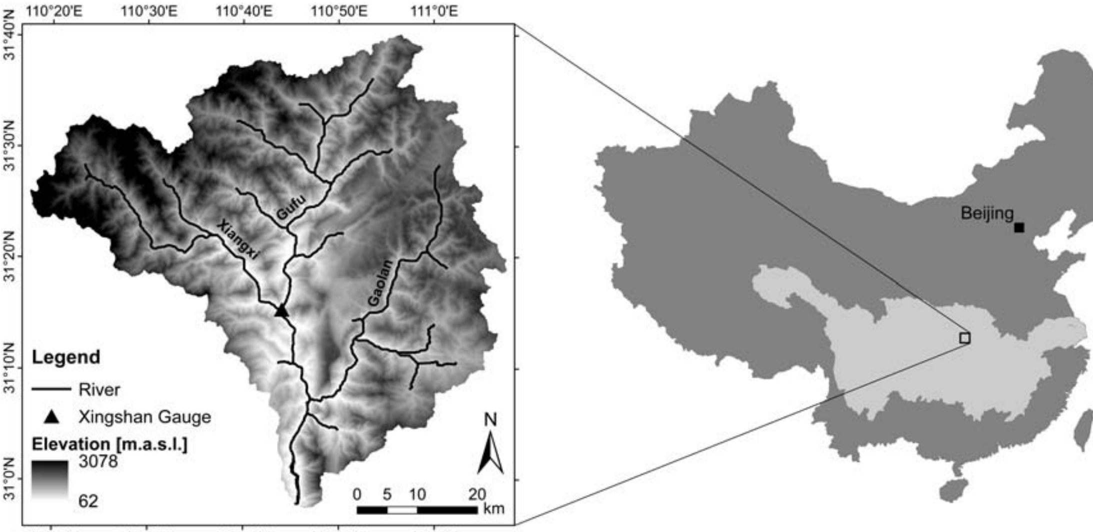

Figure 5.1: The location of the study area in China (dark grey) and the Yangtze Basin (light grey) as well as the elevation model and the river network of the Xiangxi Catchment

Land use is dominated by forest (Figure 5.2), which occupied 84% of the watershed in 1987 (Seeber et al. 2010). Agriculturally used areas are restricted to small areas, mostly in close proximity to rivers and roads. The most important crops are corn, rapeseed, sweet potatoes, cabbage, tobacco and rice. On higher altitudes in the northern part of the watershed, tea is grown as a cash crop, while in the southern part of the watershed orange plantations are covering large proportions of the agriculturally used areas. The dominant soil types are Limestone soils and Yellowbrown soils (Genetic Soil Classification of China), which occupy 38 and 41% of the watershed, respectively, according to a soil map digitized from analog soil maps of the counties Shennongjia, Xingshan, and Zigui on a scale of 1:160,000/1:180,000 (Schönbrodt-Stitt et al. 2012) (Figure 5.2).

The climate in the Xiangxi Catchment is characterized by the subtropical summer monsoon, which causes the summers to be warm and humid with abundant rainfall. Approximately 80% of the average annual precipitation of 1000 mm (1961-1990) occurs during the wet season from April to September. In winter, precipitation is very low. The average annual temperature is 16.9°C (1961-1990). Precipitation and temperature are characterized by a strong variability with altitude (He et al. 2003). In accordance with the seasonality of the climate, runoff and soil erosion mainly occur during summer (Ng et al. 2008; Shen et al. 2010b). The mean annual streamflow at Xingshan Gauge amounts to 36.75 $m^3 s^{-1}$ (1970-2005).

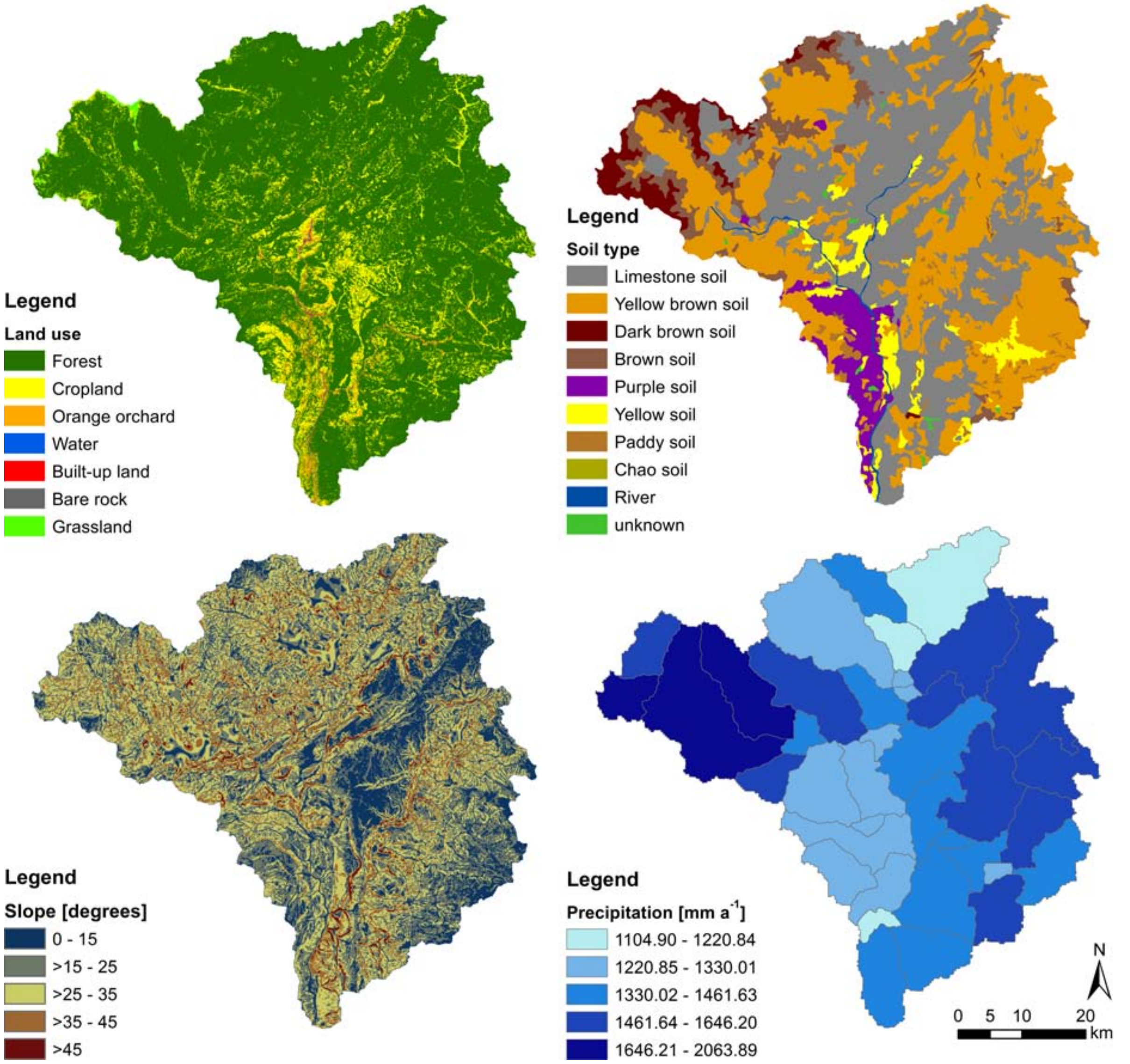

Figure 5.2: Land use (upper left), soil types (upper right) and slope classes (lower left) in the Xiangxi Catchment and precipitation per subbasin (lower right)

5.2.3 SWAT model setup for the Xiangxi Catchment

The watershed delineation for the Xiangxi Catchment is based the SRTM-DEM (Jarvis et al. 2008) with a resolution of 90 x 90 m. The watershed was divided into 38 subbasins ranging in size between 7.2 and 248.7 km^2. The land use map used to set up SWAT was classified from a Landsat image from the year 1987 (Seeber et al. 2010). As its resolution is too coarse to capture the small-scale patterns of agricultural land use in the Xiangxi Catchment, crop rotations and management schedules were simplified in SWAT. Only the most frequently occurring crop rotation, a one-year rotation of rapeseed and corn, was implemented in the model. Data required for the SWAT soil database were obtained from internet (China Soil Scientific Database 2010) and literature resources (Guo et al. 2008; Schönbrodt et al. 2010). Slopes were calculated from the DEM and divided into slope classes 1 (<15°), 2 (15-25°), 3 (25-35°), 4 (35-45°) and 5 (>45°), which are covering 20, 34, 32, 12 and 2% of the watershed, respectively (Figure 5.2).

Climate data (precipitation, temperature, relative humidity, wind speed and sunshine duration) were provided by the National Climate Centre of the China Meteorological Administration and have been subject to a thorough quality check (Feng et al. 2004). Data are available for three climate stations, of which one (Xingshan) is located within and two (Shennongjia and Zigui) are located outside the watershed, but closely enough to be considered by SWAT for selected subbasins. Sunshine duration was used to calculate solar radiation according to a method developed by Bahel et al. (1987). Time series of daily climate data are available for all three climate stations from 1975 through 2007. To account for the increase in precipitation with elevation that can typically be observed in mountainous regions, elevation bands were implemented in the SWAT model for the Xiangxi Catchment as proposed by Fontaine et al. (2002). This results in differences between the average annual amounts of precipitation in different subbasins (Figure 5.2). The SWAT model setup for the Xiangxi Catchment is presented in detail by Bieger et al. (2012).

Observed daily streamflow data for Xingshan Gauge are available from 1970 through 2005 with data for the years 1975 and 1987 missing. To match the simulation period temporally with the land use map from 1987, the calibration and validation periods for streamflow were scheduled from 1981 through 1986 and from 1988 through 1993, respectively. The time series of observed sediment loads at Xingshan Gauge ends in 1986, so sediment was calibrated for the years 1981 through 1983 and validated for the years 1984 through 1986.

The model performance was evaluated by means of visual comparison and the use of different model evaluation statistics. Following the recommendations by Legates and McCabe (1999) and Moriasi et al. (2007) for the selection of statistical criteria, the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), the coefficient of determination (R^2) and the percent bias (PBIAS) were used in this study. Model performance for monthly streamflow and sediment loads was rated according to the performance ratings proposed by Moriasi et al. (2007).

5.2.4 Plausibility check of model output at HRU level

The plausibility of model output at HRU level is analyzed in this study in regard to average annual surface runoff and sediment yield. The basic approach is to check whether spatial variations of surface runoff and sediment yield are reasonable in relation to variations in land use, soil type and slope. For this, three basic rules were defined based on expert knowledge. Surface runoff and sediment yield are assumed to exhibit the following trends:

- forest < orange orchard < cropland,
- Yellowbrown soil < Limestone soil,
- slope class 1 (<15°) < 2 (15-25°) < 3 (25-35°) < 4 (35-45°) < 5 (>45°).

Forest is characterized by a denser vegetation cover than agriculturally used areas. This results in higher interception and evapotranspiration and in lower amounts of surface runoff (Fohrer et al. 2001). Also, the vegetation cover reduces the erosive energy of precipitation and protects the soil from erosion (Lal 2001). Meng et al. (2001) show that runoff and sediment yield from orchards are lower than from cropland. The Limestone soils in the Xiangxi Catchment are characterized by a high clay content, while the Yellowbrown soils are mostly composed of silt and sand (Schönbrodt-Stitt et al. 2012). Accordingly, the hydraulic conductivity of Limestone soils is lower, which leads to a lower infiltration capacity and higher surface runoff rates as compared to the Yellowbrown soils. On steeper slopes, the gradient of the surface allows for very little storage of water in depressions, which results in a stronger and quicker initiation of surface runoff. Slope gradient also strongly affects soil erosion (Li et al. 2010). Shi et al. (2004) demonstrate that soil loss from sloping cropland was twice as high as soil loss from relatively flat cropland.

5.2.5 Modifications to the SWAT model setup

To improve the plausibility of the dependence of surface runoff on slope, two minor modifications were applied to SWAT algorithms and two parameters were recalibrated:

- Modification A: Minor modifications to the equation used for the slope adjustment of CN (Equation 5.3),
- Modification B: Minor modification to the equation used for calculating lateral flow (Equation 5.6),

- Modification C: Recalibration of the hillslope length for lateral flow in the HRUs,
- Modification D: Change of method used to vary the retention parameter in the CN method.

First, all four modifications were applied separately to assess their impact on the average amounts of surface runoff per slope class. Second, two additional variants of the original SWAT model setup for the Xiangxi Catchment were developed by applying combinations of Modifications A, B and C (Variant I) and Modifications A, B and D (Variant II).

5.3 Results and discussion

5.3.1 Results of model calibration

The calibration of streamflow resulted in a good agreement of simulated and observed data as indicated by the model evaluation statistics given in Table 5.1. According to performance ratings proposed by Moriasi et al. (2007), based on NSE and PBIAS the monthly streamflow simulation can be rated as very good for both the calibration and the validation periods. SWAT reproduces the annual and inter-annual variations of discharge generally very well. With regard to sediment loads, NSE and PBIAS indicate satisfactory and good performance, respectively, for the calibration period. During the validation period, model performance is considerably lower and has to be rated as unsatisfactory according to NSE (Table 1). The most important reasons for uncertainty in the streamflow and sediment load simulations are discussed in detail by Bieger et al. (2012).

Table 5.1: Model evaluation statistics and performance ratings according to Moriasi et al. (2007) for monthly streamflow and sediment loads

Model evaluation statistic	**Monthly streamflow [m^3 s^{-1}]**		**Monthly sediment load [t d^{-1}]**	
	Calibration	**Validation**	**Calibration**	**Validation**
NSE	0.84	0.82	0.48	0.07
R^2	0.89	0.82	0.78	0.15
PBIAS	7.99	2.01	27.4	48.2

5.3.2 Average annual surface runoff and sediment yield in the HRUs

The scarce database and the relatively coarse resolution of the land use map currently available for the Xiangxi Catchment do not allow for an implementation of complex land use patterns in SWAT. Accordingly, there is no distinction of different kinds of forest, orchards or cropland in the model. Differences in surface runoff and sediment yield between HRUs can only be attributed to differences in land use type, soil type or slope class and not to differences between individual crops or kinds of forest. This provides the opportunity to examine the plausibility of SWAT simulated surface runoff and sediment yields without complex land use patterns and parameterizations complicating the analysis.

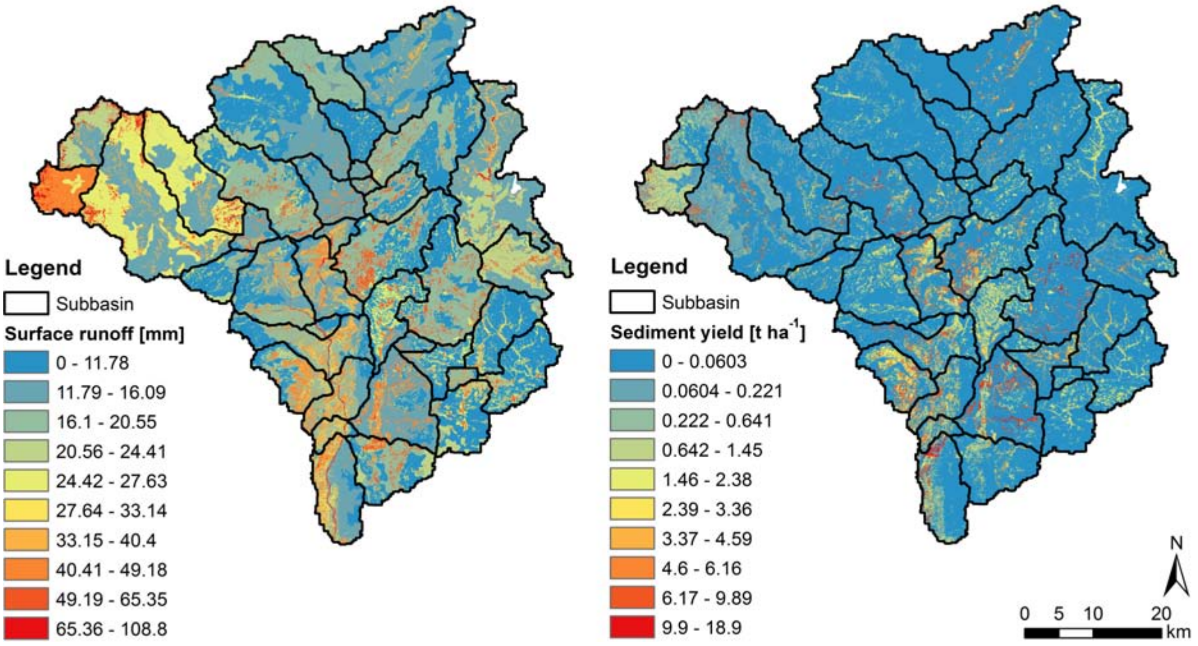

Figure 5.3: Average annual surface runoff and sediment yield in the HRUs

5.3.2.1 Dependence of surface runoff and sediment yield on land use

Figure 5.3 shows that both surface runoff and sediment yield exhibit a clear dependence on land use and variations are consistent with the parameterization of the land use types in SWAT. Generally, the lowest average annual surface runoff and sediment yield in the Xiangxi Catchment are calculated for forest, whereas the highest values occur on cropland. The average annual surface runoff from forest, orange orchards and cropland HRUs amounts to 204, 283 and 549 mm, respectively. The average annual sediment yield is 0.2, 1.6 and 15.5 t ha^{-1}, respectively, for forest, orange orchards and cropland. The remaining land use types occurring in the Xiangxi Catchment were excluded from this analysis as they occupy marginal fractions of the watershed area (Seeber et al. 2012) and can therefore be neglected. Forest yields the smallest amounts of surface runoff and sediment, because the ET from forest is higher than from orange orchards and cropland, while the CN values are lower. Sediment yields are additionally influenced by the USLE C factor which is very low for forest, medium for orange orchards and relatively high for cropland (Shi et al. 2004). Accordingly, surface runoff and sediment yield from orange orchards are higher than from forest, but considerably lower than from cropland.

5.3.2.2 Dependence of surface runoff and sediment yield on soil type

Figure 5.3 shows a clear dependence of surface runoff on the soil types occurring in the Xiangxi Catchment, which can be explained by the model parameterization. The amount of surface runoff depends strongly on the moisture content of the soil, which in turn is influenced by the depth of the soil layer, the soil texture and the soil parameters bulk density, saturated hydraulic conductivity and available water capacity. The two dominant soil types in the Xiangxi Catchment, Limestone soils and Yellowbrown soils, show considerable differences in their texture. While the Limestone soils are characterized by a high clay content, the texture of the Yellowbrown soils is mostly composed of silt and sand (Schönbrodt-Stitt et al. 2012). Because of the high proportion of small grain size fractions, the hydraulic conductivity and the bulk density of the Limestone soils are lower than the hydraulic conductivity and the bulk density of the Yellowbrown soils, whereas the available water capacity is higher. As a consequence, the Limestone soils were placed in hydrologic group C and the Yellowbrown soils belong to hydrologic group B. Therefore, a higher CN was assigned to the Limestone soils, leading to higher surface runoff rates as compared to the Yellowbrown soils.

The results for sediment yields do not indicate considerable differences depending on soil type Figure 5.3). While the Limestone soil in the Xiangxi Catchment is characterized by higher surface runoff than the Yellowbrown soil, it has a lower erodibility (Schönbrodt-Stitt et al. 2012). The effects of surface runoff and soil erodibility seem to balance out, so the variation of sediment yield between the two dominant soil types is very low. A relatively strong variation of sediment yields with soil type is detectable in the northwest of the Xiangxi Catchment, which is part of the Shennongjia Mountains. The Brown and Darkbrown soils occurring in this part of the watershed are characterized by a very high erodibility (Schönbrodt-Stitt et al. 2012), which leads to above average sediment yields.

5.3.2.3 Dependence of surface runoff and sediment yield on precipitation

As mentioned in Chapter 5.2.3, elevation bands were implemented in the SWAT model setup for the Xiangxi Catchment to account for an increase in precipitation with elevation. This results in differences between the amounts of precipitation calculated for the individual subbasins, because the precipitation observed at the climate station is adapted based on the fraction of different elevation bands within a subbasin. As surface runoff is induced by rainfall, the average annual surface runoff in the subbasins is strongly correlated with subbasin precipitation (R=0.79). Accordingly, the subbasin delineation is clearly identifiable from the surface runoff map in Figure 5.3. The highest surface runoff occurs in subbasins that are located on the highest elevations, i.e. the subbasins located in the Shennongjia Mountains in the northwest of the Xiangxi Catchment.

5.3.2.4 Dependence of surface runoff and sediment yield on slope

Because of the mountainous character of the Xiangxi Catchment, particular importance is attached to the plausibility of changes in model output with slope. Both surface runoff and sediment yield are expected to increase with increasing slope. However, according to the SWAT output for the Xiangxi Catchment there is no clear linkage between the slope classes and the average annual surface runoff and sediment yield. Because there is a strong spatial variability of slopes in the Xiangxi Catchment, the changes in surface runoff and sediment yield with slope are difficult to detect in Figure 5.3. Therefore, average annual surface runoff and sediment yields per slope class are plotted in Figure 5.4.

Neither surface runoff nor sediment yield show the expected dependence on slope. The average annual surface runoff increases from an amount of 345 mm in slope class 1 to an amount of 355 mm in slope class 2, but then decreases to amounts of 348, 338 and 331 mm, respectively, in slope classes 3, 4 and 5. The average annual sediment yield increases from 4.04 t ha^{-1} in slope class 1 to 4.75 and 5.56 t ha^{-1}, respectively, in slope classes 2 and 3, but then strongly decreases to 1.88 and 0.52 t ha^{-1} in slope classes 4 and 5.

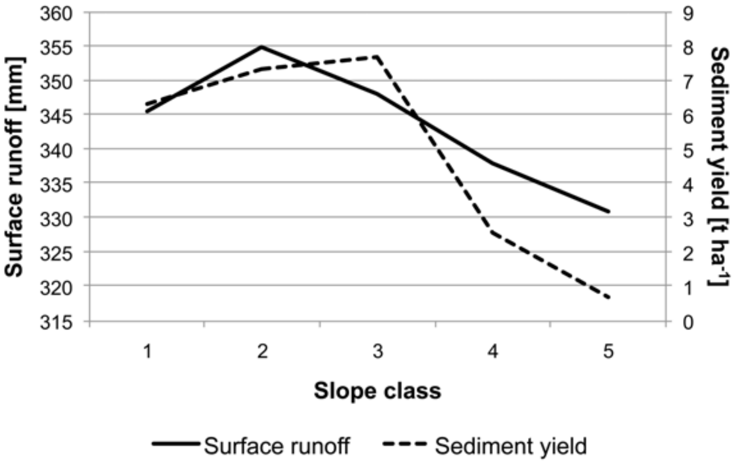

Figure 5.4: Average annual surface runoff and sediment yield per slope class

5.3.3 Improving the dependence of surface runoff on slope

Detailed analysis of SWAT output revealed that the average annual amounts of surface runoff are impacted by a number of factors including the slope adjustment of CN, calculation of lateral flow and calculation of the retention parameter used in the SCS-CN method. In the following chapters, modifications aiming at improving the dependence of surface runoff on slope and their effects are presented and discussed.

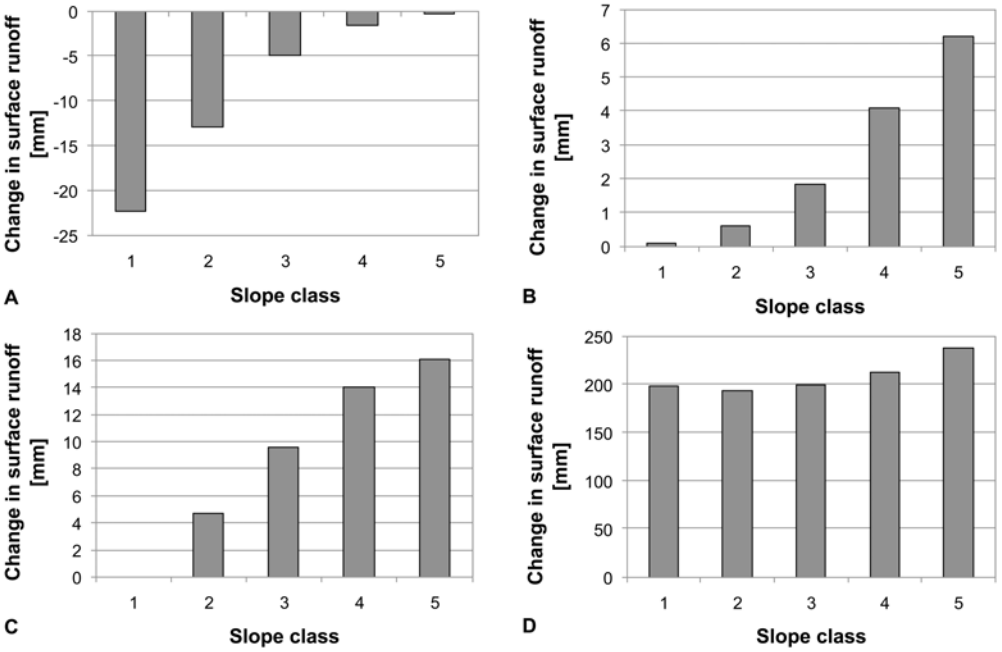

Figure 5.5: Changes in surface runoff caused by applying Modifications A, B, C and D

5.3.3.1 Modification of slope adjustment of CN values (Modification A)

The equation used by SWAT for the adjustment of CN to different slopes only accounts for slopes with a gradient of 25° or less. In many watersheds, this does not impact simulation results, as no slopes >25° occur. However, in mountainous watersheds, where slopes can even have gradients of more than 45° this may be of importance. In the Xiangxi Catchment, this affects 46% of the watershed area. To assume that CN does not increase with slope in almost half the watershed does not seem realistic. Therefore, the equation for slope adjustment of CN (Equation 5.3) was slightly modified:

$$CN_{2s}=\frac{(CN_3-CN_2)}{3}\cdot[1-1.3\cdot1.5^{(-12.941\cdot slp)}]+CN_2 \tag{5.10}$$

where CN_{2s} is the moisture condition II curve number adjusted for a given slope, CN_3 is the moisture condition III curve number for the default 5% (2.9°) slope, CN_2 is the moisture condition II curve number for the default 5% (2.9°) slope and *slp* is the average slope of the HRU. Figure 5.6 shows the adjustment of CN to increasing slopes for the original and the modified functions. While the original function causes CN to increase relatively strongly in the beginning, it starts to level off at slope gradients of about 8.5° and reaches its maximum at slope gradients of 25°. In contrast, the modified function is flatter, so that CN is increased less strongly, but consistently up to slope gradients of 45°.

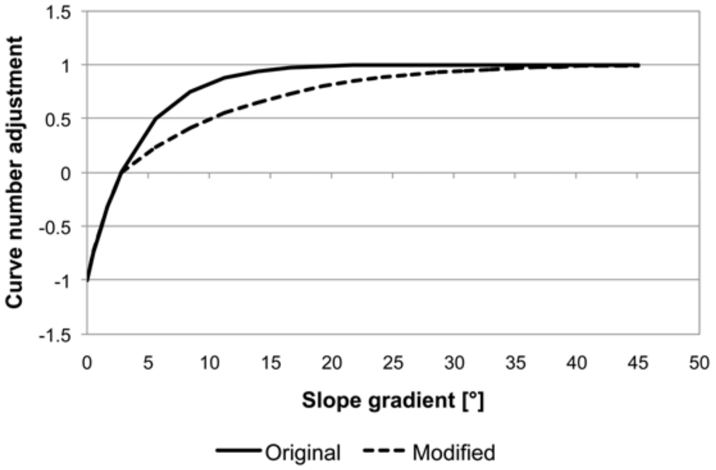

Figure 5.6: Curves of default and modified equations for the slope adjustment of CN

On average, using a flatter curve for adjusting CN leads to a reduction of surface runoff in all slope classes. The strongest reduction of surface runoff occurs in slope class 1 (-22.3 mm), whereas in slope class 5 surface runoff decreases only marginally (-0.34 mm) (Figure 5.5). Thus, Modification A has the expected effects on surface runoff. However, changes are not large enough to cause a general increase of surface runoff with increasing slope.

The objective of testing a slightly modified equation was to demonstrate the effects of the slope adjustment on the dependence of surface runoff on slope. Equation 5.10 does not have a real physical or empirical basis and is not meant to be an alternative to the equation used in SWAT. Huang et al. (2006) developed an empirical equation for slope adjustment of CN on the Loess Plateau in China. However, their equation is only valid for slopes between 8 and 54.5° and was thus not suitable for the Xiangxi Catchment.

5.3.3.2 Modification of the equation calculating lateral flow (Modification B)

In the equation used by SWAT for calculating lateral flow, the tangent of slope is assumed to equal the sine of slope. This is a reasonable assumption as long as slopes in a watershed are not very steep. The steeper a slope, the larger is the difference between its tangent and sine (Figure 5.7). When using the tangent of slope instead of the sine of slope for the calculation of the flow velocity at the outlet, the amount of lateral flow in HRUs with steep slopes is overestimated. This leads to an underestimation of soil moisture and accordingly to an underestimation of surface runoff, which is strongly dependent on soil moisture when calculating the retention parameter as a function of soil water content. Therefore, the term *slp* in Equation 5.6, which equals the tangent of the slope, is replaced by the sine of the slope as originally required for the calculation of flow velocity (Equation 5.7) to more accurately estimate the lateral flow on steep slopes.

By modifying the equation used for the calculation of lateral flow and using the sine of slope instead of the tangent of slope, lateral flow is reduced on steep slopes and accordingly, soil moisture and surface runoff are increased. In the Xiangxi Catchment, the changes in surface runoff induced by Modification B range from 0.1 mm in slope class 1 to 6.2 mm in slope class 5 (Figure 5.5). Again, changes are too small to improve the plausibility of average annual surface runoff per slope class. Even by combining Modifications A and B it was not possible to achieve a plausible increase of surface runoff with slope.

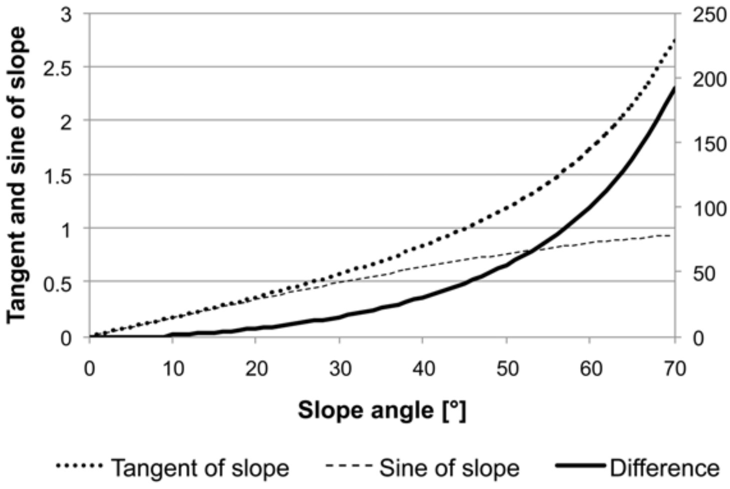

Figure 5.7: Differences between tangent and sine of slope angle

5.3.3.3 Recalibration of the parameter SLSOIL (Modification C)

The parameter SLSOIL (input file *.hru) describes the slope length of an HRU (L_{hill} in Equation 5.6) and is used for the calculation of lateral flow. It strongly impacts the amount of lateral flow generated in an HRU. By default, SLSOIL equals the parameter SLSUBBSN, which is assigned the same value for all HRUs in a subbasin (Neitsch et al. 2011). In contrast, an individual slope gradient (HRU_SLP in the input file *.hru and *slp* in Equation 5.6) is calculated for each HRU by the ArcSWAT interface based on the DEM. The larger the ratio of HRU_SLP to SLSOIL and thus of slope gradient to slope length, the larger is the amount of lateral flow. Therefore, when using the default values assigned to the parameters HRU_SLP and SLSOIL by the ArcSWAT interface, lateral flow is higher in HRUs with a steeper average slope. During the initial calibration of the SWAT model for the Xiangxi Catchment, SLSOIL was set to a value of 20 m in the entire watershed. In this study, the initial value is only used for HRUs that belong to slope class 1. For slope classes 2, 3, 4 and 5, SLSOIL was increased by 20, 40, 60 and 80 m, respectively.

While according to general hydrologic knowledge an increase of lateral flow with slope is considered realistic, in SWAT it leads to an increasing underestimation of surface runoff with increasing slope gradients. The algorithms currently implemented in SWAT allow for an indirect impact of lateral flow on surface runoff by impacting soil water content. Therefore, a simultaneous increase of lateral flow and surface runoff with slope gradient is difficult to achieve in the model. Depending on the scope of a study and the characteristics of a watershed, the focus can be laid on a plausible representation of either surface runoff or lateral flow. As this study is not only concerned with runoff, but also with sediment yields, a realistic representation of the spatial variation of surface runoff is considered to be of particular importance. Therefore, the slope length parameter SLSOIL was recalibrated. Slope length was not changed for HRUs in slope class 1, so surface runoff in this slope class did not change. In slope classes 2, 3, 4 and 5, surface runoff increased by 4.7, 9.5, 14.0 and 16.1 mm, respectively (Figure 5.5). However, changes in surface runoff induced by Modification C are not large enough to improve the plausibility of the dependence of surface runoff on slope. Even though this seems to be a convenient way of calibrating surface runoff to achieve the desired spatial variation of this flow component within a watershed, there are some objections to increasing SLSOIL arbitrarily. According to Neitsch et al. (2010), 90 m is considered to be a very long slope length. When increasing slope length by 20 m per slope class, it is already 100 m in slope class 5. Any further increase would therefore lead to slope lengths beyond the range recommended by Neitsch et al. (2010). Generally, slope length is very difficult to calculate and is not solely dependent on slope gradient (Hickey 2000). Accordingly, there is no real justification for introducing a direct correlation between slope gradient and slope length in SWAT.

5.3.3.4 Recalibration of the parameter ICN (Modification D)

The parameter that determines which method is used for varying the daily retention parameter for calculating surface runoff is called ICN (input file *.bsn). The basic calibration of SWAT was done using the default method where the retention parameter is calculated based on the soil profile water content. The option to use plant ET instead of soil water content to vary the retention parameter for the SCS-CN method was implemented in SWAT because runoff was proven to often be too high on shallow soils (Neitsch et al. 2011). In this study, it was used as a way to achieve a plausible increase of surface runoff with slope without having to accept a simultaneous, unrealistic decrease in lateral flow. When using the plant ET method the retention parameter and thus the surface runoff is less dependent on soil moisture and more dependent on antecedent climate (Neitsch et al. 2011). Modification D caused surface runoff in the Xiangxi Catchment to increase considerably by amounts of 193 to 238 mm (Figure 5.5). However, in this case the smallest change did not occur in slope class 1, but in slope class 2. Therefore, a change of the method used for the calculation of the retention parameter alone did not yield a consistent increase in average annual surface runoff with slope.

5.3.3.5 Combinations of SWAT model setup modifications (Variants I and II)

The results for Variant I indicate that the modifications to the SWAT model setup for the Xiangxi Catchment led to a decrease of average annual sediment yields in slope classes 1 and 2 and to an increase in slope classes 3 to 5 as compared to the original model parameterization. However, the increase in slope classes 4 and 5 is not strong enough, so the average annual sediment yield still decreases slightly from 353 mm in slope class 3 to 351 and 348 mm in slope classes 4 and 5. In slope classes 1 and 2 it amounts to 323 and 347 mm, respectively (Figure 5.8). It can be assumed that a further increase of SLSOIL for slope classes 4 and 5 would result in a consistent increase of average annual surface runoff with slope, but as discussed above this is not considered to be a reasonable means of producing the desired effects.

Varying the retention parameter as a function of plant ET instead of soil water content results in higher amounts of surface runoff in Variant II than in both the original model parameterization and Variant I. In combination with the changes to the equations for slope adjustment and lateral flow calculation, it achieves a plausible and consistent increase in average annual surface runoff from 535 mm in slope class 1 to 569 mm in slope class 5 (Figure 5.8).

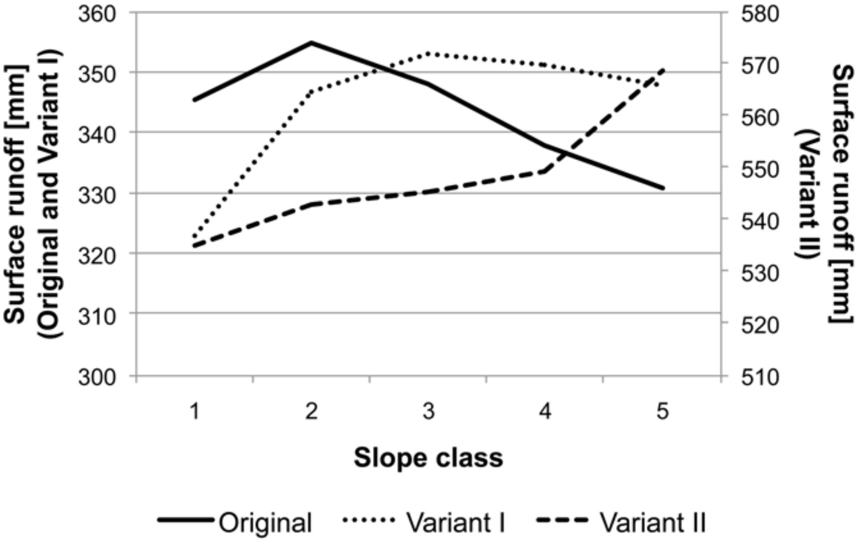

Figure 5.8: Average annual surface runoff per slope class for the original SWAT model setup and the modified versions Variant I and Variant II

Figure 5.9 shows the influence of the two variants on the proportions of ET and water yield and of the three flow components surface runoff, lateral flow and groundwater flow. The results indicate that effects on ET and water yield are very small. Compared to the original model setup, the proportion of ET is marginally higher in Variant I and lower in Variant II, whereas the proportion of water yield changes inversely. In contrast, the two variants cause considerable changes in the proportions of the different flow components.

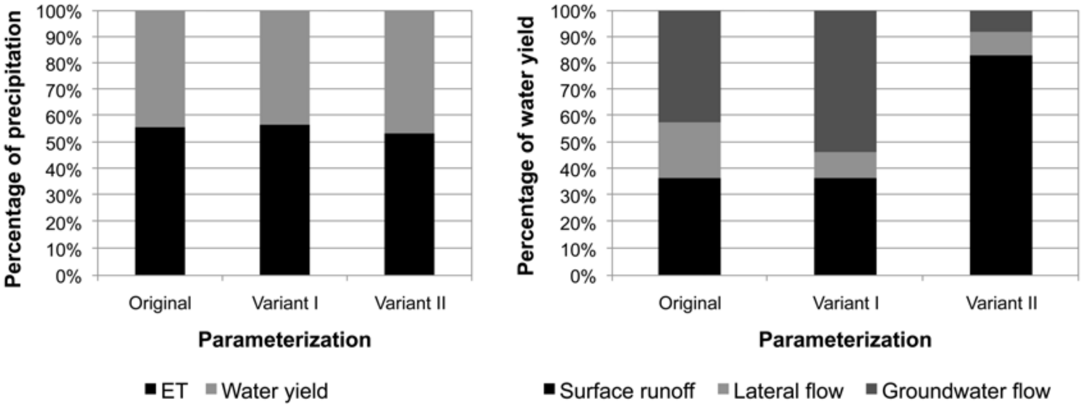

Figure 5.9: Proportions of ET and water yield and of the three flow components surface runoff, lateral flow and groundwater flow for the original model setup, Variant I and Variant II

Variant I results in a strong decrease of lateral flow from 21 to 10% of water yield. While this leads to a negligible overall increase of surface runoff from 36.5 to 36.6%, groundwater flow increases strongly from 42 to 54% of water yield. This indicates that the reduction of lateral flow leads to a larger amount of soil water that is available for percolation to the groundwater whereas it caused a spatial redistribution instead of an overall increase of surface runoff. There are no observations of surface runoff, lateral flow or groundwater flow available for the Xiangxi Catchment, so it is generally difficult to validate the simulated proportions of flow components. Due to the mountainous terrain, a large proportion of surface runoff is considered to be reasonable and the underlying geology can justify large amounts of groundwater flow. However, the shallow soils with underlying impermeable layers of rock prevalent in the watershed suggest that lateral flow might also be of some importance in the Xiangxi Catchment. To determine which of the estimates is most accurate, field measurements of different flow components in the Xiangxi Catchment would be necessary.

Variant II leads to a strong increase of the proportion of surface runoff to 83%. With proportions of 9 and 8%, respectively, lateral and groundwater flow are only of minor importance in Variant II. This is clearly not realistic and can be explained by the initial calibration of the model which was focused on using the soil water content method to vary the retention parameter. Parameters controlling the proportion of flow components have not been recalibrated for Variant II as this was beyond the scope of the current study. Nevertheless, when the model is calibrated accordingly, the plant ET method is assumed to yield better results for the Xiangxi Catchment than the soil water content method. This will be subject to further research in the future. The results of this study demonstrate that it is crucial to select the most suitable method for the variation of the retention parameter in the very early stages of model calibration.

The use of the SCS-CN method to calculate surface runoff in watershed models is generally discussed controversially (Garen and Moore 2005). Gassman et al. (2007) point out that modifying the SCS-CN method or integrating more complex methods for the estimation of surface runoff in SWAT could improve model predictions. However, because it is relatively easy to parameterize, the SCS-CN method is still the method of choice for surface runoff computation in a number of watershed models.

5.3.4 Factors influencing the dependence of sediment yield on slope

The adjustments to the SWAT model that were made to improve the dependence of surface runoff on slope were expected to influence the sediment yields as well. However, results demonstrate that the effects of Variant I on sediment yields are marginal. Average annual sediment yields from slope class 1 decreased by 0.3 t ha^{-1} and the changes are even smaller in the remaining slope classes. Therefore, average annual sediment yields still increase from slope class 1 to slope classes 2 and 3, but then strongly decrease in slope classes 4 and 5. Because of the higher surface runoff, Variant II generally results in higher sediment yields, but the differences between the five slope classes follow the same pattern. Average annual sediment yields increase from 7.8 t ha^{-1} in slope class 1 to 9.2 and 9.9 t ha^{-1} in slope classes 2 and 3 and then decrease to 3.6 and 1.0 t ha^{-1} in slope classes 4 and 5 (Figure 5.10). The key factor dominating the average sediment yields per slope class is the average HRU area. As shown in Figure 10, on watershed average the HRU size per slope class increases from 0.8 km^2 in slope class 1 to 1.4 and 1.5 km^2 in slope classes 2 and 3, but then decreases significantly to 0.8 and 0.3 km^2 in slope classes 4 and 5.

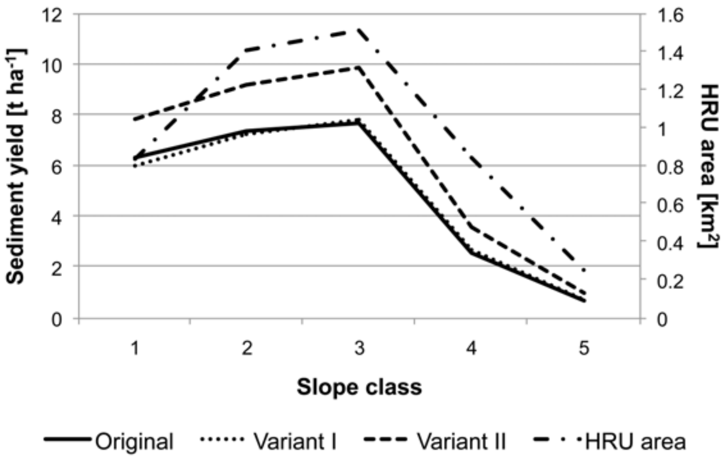

Figure 5.10: Average annual sediment yield per slope class for the original model parameterization, Variant I and Variant II and average HRU area per slope class

The effects of HRU area on sediment estimations in SWAT has been analyzed and discussed in detail by FitzHugh and Mackay (2000) and Chen and Mackay (2004). FitzHugh and Mackay (2000) show that there is a non-linear relationship between sediment and HRU area and that sediment yield varies proportionally with the HRU area raised to the 1.12 power. They point out, that the influence of the MUSLE soil erodibility, cover and management, support practice, topographic and coarse fragment factors is only secondary compared to the influence of the HRU area. An option for minimizing the effect of HRU area on sediment yields is to delineate the watershed into very small subbasins, which will reduce the size of HRUs as well (Chen and Mackay 2004). Arabi et al. (2006) recommend delineating a watershed into subbasins that cover a maximum of 4% of the total watershed area. Migliaccio and Chaubey (2008) defined an even stricter limit for the subbasin size of 2% of the total watershed area to improve sediment loads predictions. Haverkamp et al. (2005) developed a tool to identify an appropriate level of discretization based on the entropy of a watershed, which allows for a better consideration of the heterogeneity of the watershed.

The close relationship between the watershed average annual sediment yield and HRU area in this study confirms the conclusions drawn by FitzHugh and Mackay (2000). However, sediment yields from the three dominant land use types forest, orange orchard and cropland lie in different orders of magnitude. Sediment yields from cropland are considerably higher than those from forest and orange orchards. Averaging the sediment yields for the three land use types might conceal extraordinarily high or low values. Therefore, it is reasonable to analyze the average annual sediment yields per slope class separately for forest, orange orchards and cropland.

With regard to cropland and orange orchards, the average HRU area increases from slope class 1 to 2, but then decreases consistently in the remaining slope classes. While the sediment yield from cropland increases from slope class 1 to 3 and decreases in slope classes 4 and 5, the sediment yield from orange orchards decreases consistently from slope class 1 to 5. Regarding forest, the average HRU area increases from slope class 1 to 3 and decreases in slope classes 4 and 5, whereas the sediment yield increases from slope class 1 to 4 and only decreases in slope class 5 (Figure 11).

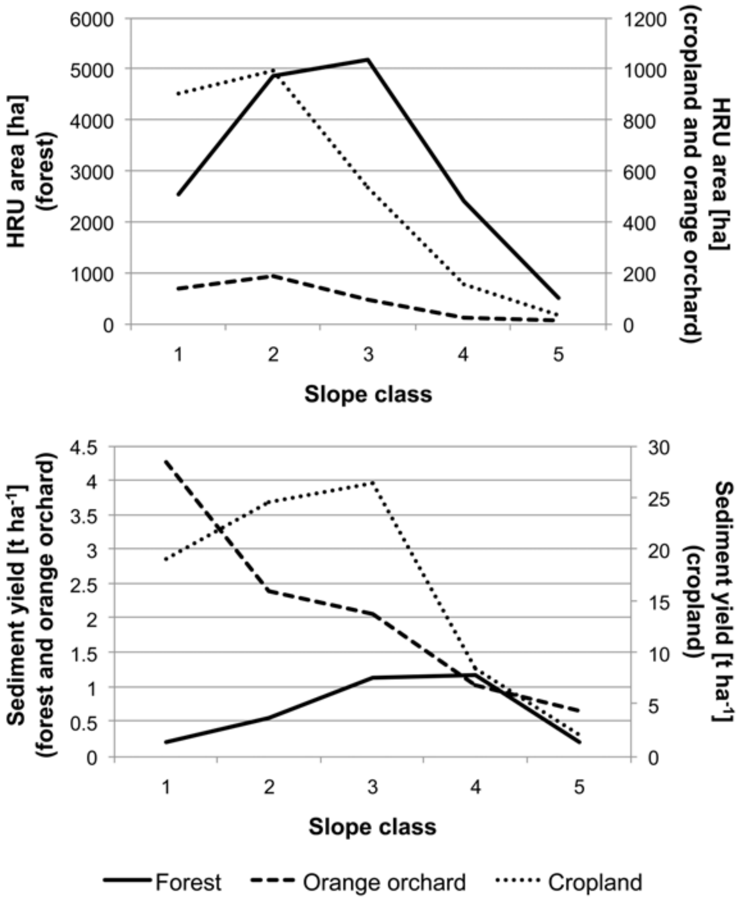

Figure 5.11: Average HRU area and average annual sediment yield per slope class for the land use types forest, orange orchard and cropland

The high average annual sediment yields from forest HRUs in slope classes 3 and 4 can be attributed to merely two HRUs per slope class which have extraordinarily high sediment yields as indicated by the outliers in Figure 5.12. These HRUs are located in the Shennongjia Mountains in the northwestern part of the Xiangxi Catchment, where highly erodible Brown and Darkbrown soils occur in combination with steep slopes and high amounts of precipitation. The same reason causes the increase in average annual sediment yields from cropland between slope classes 2 and 3, which occurs despite the decreasing average HRU area (Figure 5.12). The decrease of average annual sediment yields from orange orchards in spite of the increase in HRU area from slope class 1 to slope class 2 can be explained by a high number of relatively small HRUs with highly erodible soils, which leads to high sediment yields, but a small average HRU area (Figure 5.12).

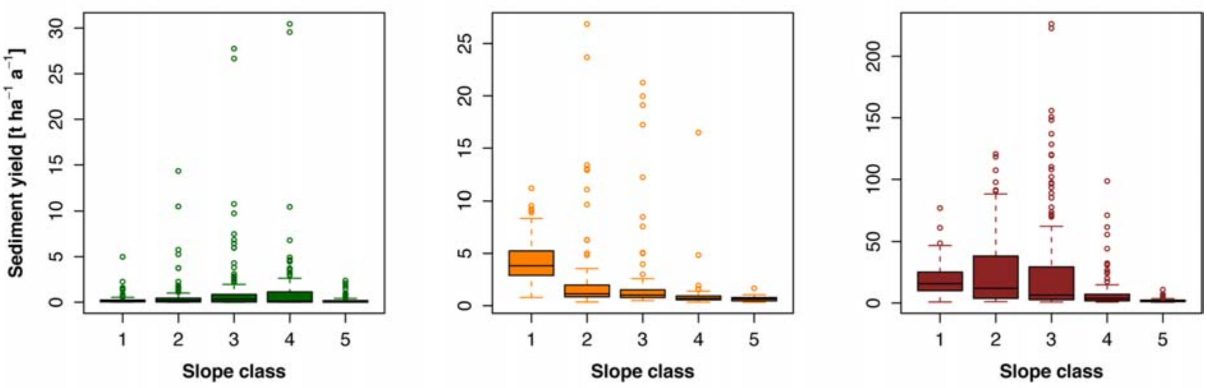

Figure 5.12: Boxplots of HRU sediment yield per slope class for the land use types forest (left), orange orchard (middle) and cropland (right)

The results of this study indicate that in the Xiangxi Catchment not only the average HRU area impacts the average annual sediment yields per slope class, even though it is the dominating factor as stated by FitzHugh and Mackay (2000). Due to its non-linear relationship with sediment yield, the HRU area exerts a strong influence on simulated sediment yields, but the other factors can add additional variation to the spatial patterns of sediment yield. This can be crucial for the identification of CSAs and the targeting of BMPs. Therefore, it is important to carefully parameterize the variables that are important for the generation of surface runoff and for the estimation of peak runoff rate as well as the MUSLE soil erodibility, cover and management, support practice, topographic and coarse fragment factors.

Some authors point out that the HRU concept of SWAT is not compatible with the MUSLE, because the MUSLE is a watershed response model, but HRUs are non-spatial subunits of a watershed (Bosch et al. 2010; Chen and Mackay 2004). They criticize the lacking interaction between HRUs on the one hand (Bosch et al. 2010) and the artificial connectivity resulting from combining non-adjacent areas within a subbasin into one single HRU on the other hand (Chen and Mackay 2004). Another shortcoming in SWAT is the lack of runoff and sediment routing through the landscape. This can be allowed for by running SWAT based on grid cells and thus transforming SWAT into a fully distributed model. Rathjens and Oppelt (2012) developed an interface for setting up grid-based SWAT models and tested it in a watershed in North Germany. Another approach is the landscape routing by Arnold et al. (2010) which is currently being tested in a number of watersheds and which is expected to provide better estimates of the impact of land use change and BMPs across the watershed (Arnold et al. 2010; Bosch et al. 2010).

5.4 Conclusion

This study has demonstrated that in spite of a reasonable model performance with regard to streamflow and sediment load simulations at Xingshan Gauge, the spatial variability of surface runoff and sediment yields in Xiangxi Catchment is not consistently plausible. While the variations of surface runoff and sediment loads with land use and soil types can be explained with the parameterization of the dominant land use and soil types, neither surface runoff nor sediment yields showed a plausible increase with increasing slope gradients. The modifications of the original SWAT model setup for the Xiangxi Catchment tested in this study improved the plausibility of surface runoff considerably. However, they did not have a strong impact on sediment yields.

The following conclusions can be drawn from this study:

1. It is highly recommendable to conduct a detailed analysis of model output at HRU level during model calibration. This is of particular importance when SWAT is used as a tool to identify CSAs for targeting BMPs. Also, a detailed analysis of the plausibility of SWAT output at HRU level can help to validate model simulations in watersheds where there is little observed data available for extensive model calibration and validation. A general plausibility check can easily be done based on expert knowledge.

2. In mountainous watersheds, a particular focus should be laid on the dependence of surface runoff and sediment yield on slope.

3. The plausibility of surface runoff can be improved by carefully analyzing all processes directly and indirectly influencing the generation of surface runoff in the model and subsequently modifying the key algorithms and parameters.
4. For ensuring a plausible representation of the spatial variation of sediment yield in SWAT, an appropriate level of watershed discretization and reasonable parameterization of all MUSLE factors is crucial.

5.5 Acknowledgements

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Chapter 6

Discussion of central findings

6.1 Summarizing answers to research questions

The main objective of this dissertation was to lay the groundwork for applying SWAT in the Three Gorges Region in China to evaluate the effects of past, present and future changes in land use patterns on water quantity and quality. Due to the limited amount of available data, this poses a particular challenge in the Xiangxi Catchment. Nevertheless, the main objective was achieved and the research questions posed in Chapter 1.4 can be answered satisfactorily.

Research question 1: Can analysis of observed data and uncalibrated model output help to acquire valuable information about key hydrological processes to promote SWAT model calibration in the Xiangxi Catchment?

This research question was addressed in Chapter 2, which presents a methodology for evaluating model output in order to identify processes governing the hydrological behavior of a watershed. In many watersheds, this kind of information can be derived from extensive observed data. However, this is not possible in watersheds like the Xiangxi Catchment, where the amount of observed data available is limited. Therefore, the applicability of residual analysis as well as the analysis of auto- and cross-correlations for model evaluation in addition to the common model evaluation criteria was tested as a tool to identify important hydrological processes in the Xiangxi Catchment prior to model calibration. Results demonstrate, that residual analysis is helpful for identifying timing errors of streamflow peaks and seasonal variations in model performance. It reveals, which parts of the hydrograph are characterized by the largest residuals (e.g. rising or falling limbs of flood hydrographs, low flows or high flows). The analysis of auto- and cross-correlations provides valuable insights into a watershed's response to precipitation events by allowing for a comparison of the dependence of observed and simulated streamflow on precipitation or streamflow on the previous days. The analysis of residuals and auto- and cross-correlations is not limited to the parameters included in Chapter 2. Further application of both techniques can possibly help to extract even more information from the available data.

Research question 2: Is SWAT capable of adequately simulating water balance, streamflow and sediment yield in the Xiangxi Catchment in the Three Gorges Region under past land use conditions?

This research question was the main focus of Chapter 3, in which the basic application of the SWAT model to the Xiangxi Catchment is presented. The model was set up using the land use map from 1987 and model performance during calibration (1981-1986) and validation (1988-1993) was evaluated at watershed level using the common statistical criteria and visual comparison. The most important sources of uncertainty in the model output were listed in Chapter 3, especially with regard to sediment loads at Xingshan Gauge. Results indicate that SWAT performs very well with regard to streamflow simulations at the gauge and is able to depict the water balance in the Xiangxi Catchment reasonably well, whereas sediment predictions are more problematic. One important source of model error that strongly affects both streamflow and sediment simulations is the inadequate representation of spatial rainfall variability by the three available climate stations. Sediment load predictions are assumed to be influenced by a number of additional factor that add further model error and reduce model performance. The results presented in Chapter 3 demonstrate that SWAT is generally able to simulate the processes related to hydrology and sediment transport in the Xiangxi Catchment. However, they also stress the importance of a thorough analysis of model uncertainty. The most important sources of uncertainty in the SWAT model results for the Xiangxi Catchment are summarized in a separate chapter (Chapter 6.2) below.

Research question 3: Can the model be used to simulate land use scenarios for assessing the impacts of the large-scale land use change in the Three Gorges Region on water balance, streamflow and sediment yield?

Answering this research question was the central aim of Chapter 4, which presents a preliminary assessment of the impacts of land use change on hydrology and sediment transport in the Xiangxi Catchment. Based on the model calibration using the land use map from 1987 (Chapter 3), SWAT was used to simulate land use scenarios using the land use maps from 1999 and 2007 as well as three hypothetical land use maps. The impacts of different land use patterns on water balance, streamflow and sediment yield were analyzed at watershed and subbasin level. Contrary to expectations, the Xiangxi Catchment was characterized by an increase in forested areas between 1987 and 2007, which resulted in a decrease of fast runoff components and sediment yield and an increase in groundwater flow.

Scenario 1 assumed a further increase in forest, which led to a further decrease of surface runoff and sediment yield. In contrast, Scenario 2 and Scenario 3 assumed an increase in cropland and orange orchards and resulted in higher amounts of surface runoff and sediment yield. Generally, the model shows the expected response to changes in land use and depicts the spatial variation within the watershed reasonably well. Subbasins with higher fractions of agriculturally used areas are characterized by larger sediment yields and differences in model output between the scenarios can be explained by changes in the proportions of different land use types. This indicates that SWAT is generally able to simulate land use scenarios in the Xiangxi Catchment.

Research question 4: How does the model perform at HRU level, i.e. the spatial scale that is most relevant for the identification of Critical Source Areas and the application of conservation measures?

This research question was investigated in Chapter 5, which presents a detailed analysis of SWAT simulated surface runoff and sediment yield at HRU level. In the Xiangxi Catchment, the fraction of forested area is very high in most of the subbasins. Therefore, subbasin averages are of limited suitability for identifying Critical Sources Areas and targeting Best Management Practices. At HRU level, specific combinations of land use, soil type and slope can be identified, which contribute extraordinarily high amounts of sediment to the average watershed yield. Also, analysis of SWAT output at HRU level can help to check plausibility of model output and identify further sources of uncertainty. Results demonstrate that SWAT simulated surface runoff and sediment yield exhibit reasonable differences as a function of land use and soil types. However, the dependence of both surface runoff and sediment yield on slope is less plausible. The reasons for this are discussed in detail and ways to improve the plausibility of model results are presented in Chapter 5. While some inconsistencies can be attributed to inadequate model parameterization, others are caused by the algorithms chosen to represent natural processes in the model. Analysis of model output at HRU level has proven to be essential for identifying Critical Source Areas in the Xiangxi Catchment. Also, it has been shown to be a good means of performing an additional plausibility check that can complement standard model evaluation, especially in data-scarce watersheds, where observed data for model calibration and validation is limited.

Research question 5: What are the most important deficits of the SWAT model setup, parameterization and calibration for the Xiangxi Catchment?

This can be regarded as the central research question that interlinks all parts of this dissertation. All watershed models are approximate representations of complex natural systems (Kalin and Hantush 2003). The algorithms used to represent hydrological processes in a model are subject to many assumptions made by the model developer. Application of a model involves further simplifications due to insufficient observed data and varying modeler's experience. Accordingly, uncertainties in the model results can originate from the input data, the model parameters and the model structure (Breuer et al. 2006; Zhang et al. 2011b, 2012a, 2012b). A detailed analysis of the deficits of model setup, parameterization and calibration should be a crucial part of all modeling studies, especially when model results are supposed to provide a scientific basis for the development of watershed management plans. In data-scarce watersheds like the Xiangxi Catchment, model error is usually higher than in watersheds where modelers can rely on a profound database of observed data for model parameterization, calibration and validation. Because of their central importance for this study, the main deficits of the SWAT model setup, parameterization and calibration for the Xiangxi Catchment are summarized in a separate chapter.

6.2 Main deficits of model setup, parameterization and calibration

One of the most important sources of error in SWAT simulations for the Xiangxi Catchment is the climate data. Especially the spatial variability of precipitation is not captured by the coarse network of climate stations, which leads to an under- or overestimation of many streamflow peaks. A small number of peaks are overestimated because a localized rainfall event at Xingshan climate station is assumed by the model to have occurred over large parts of the watershed, while most peaks are underestimated, which can be attributed to localized rainfall events in parts of the watershed that were not recorded by any of the three climate stations. Similar problems were also reported by other authors (Cao et al. 2006; Inamdar and Naumov 2006; Kirsch et al. 2002; Legesse et al. 2003), who concluded that in such situations there is no use in attempting to achieve a better fit of observed and simulated peaks. However, it may be possible to improve the representation of spatial rainfall variability by using radar data or advanced techniques for the spatial interpolation of rainfall data. Jayakrishnan et al. (2005) express concerns regarding the quality of radar data. A study by Xu et al. (2010a) revealed that using gridded climate data instead of station data did not improve SWAT streamflow estimations in the Xiangxi Catchment. It has to be pointed out that the CRU (Climatic Research Unit) data set they used is also based on station data, which were averaged for each grid cell using Thiessen polygon weights. The 5° x 5° resolution of the data set failed to provide data in a higher spatial resolution than the climate stations Xingshan, Shennongjia and Zigui. Instead, the gridded climate data introduced further uncertainty, because monthly data had to be downscaled to daily data using a weather generator (Xu et al. 2010a). In contrast, the application of different techniques for rainfall interpolation tested by Shen et al. (2012) in the neighboring Daninghe Catchment yielded quite promising results.

Another important source of model error is the number and size of subbasins a watershed is divided into. A number of authors have investigated the effects of watershed subdivision and concluded that the number and size of subbasins can cause large variations in SWAT sediment predictions, whereas streamflow predictions did not seem to be strongly affected by watershed subdivision (Arabi et al. 2006; Bingner et al. 1997; Chen and Mackay 2004; FitzHugh and Mackay 2000; Haverkamp et al. 2005; Jha et al. 2004; Migliaccio and Chaubey 2008). Jha et al. (2004) recommend including a sensitivity analysis with varying subbasin delineations in watershed modeling studies. Arabi et al. (2006) suggest to delineate a watershed into subbasins that cover a maximum of 4% of the total watershed area. Migliaccio and Chaubey (2008) define an even stricter limit for the subbasin size of 2% of the total watershed area to improve sediment loads predictions. Chen and Mackay (2004) recommend to generally use the maximum number of subbasins supported by the resolution of the DEM.

Model predictions of sediment yield have also shown to be very sensitive to the resolution of spatial input data (DEM, soil map and land use map). The resolution of the DEM affects the subbasin delineation and the calculation of topographic parameters and has been shown to impact sediment yields in studies conducted by Cotter et al. (2003), Chaplot et al. (2005) and Di Luzio et al. (2005). The spatial input data used in this study for the Xiangxi Catchment are rather coarse. In addition, soil parameters were not available for all soil types occurring in the Xiangxi Catchment, so for some parameters the same values had to be used for different soil types. This caused a further oversimplification of soil information and may have reduced the accuracy of sediment simulation results due to inadequate estimations of soil-related processes. Di Luzio et al. (2005) state that finer soil and land use maps can increase the number of HRUs and thus allow for the definition of more precise and diversified management patterns. This is assumed to be of great importance in the Xiangxi Catchment as it is characterized by small-scale agriculture. SWAT has been shown to be very sensitive to the crop rotations implemented in the model (Ullrich and Volk 2009). However, agricultural fields in the Xiangxi Catchment are mostly much smaller than the grid size of the land use map used. Additionally, because of a lack of information about crop rotations, tillage operations, and fertilizer applications, management schemes implemented in the model had to be kept very simple, which caused a further oversimplification of land use data. The inability to represent the diversity of crops and management practices at watershed scale is also pointed out as a main factor contributing to the uncertainty of model results by Shen et al. (2010a) and Huang et al. (2009a).

Additional uncertainty is introduced by the algorithms used in SWAT. In this study, the SCS-CN method used for predicting surface runoff and the MUSLE used for estimating sediment yields were examined. The use of the SCS-CN method to calculate surface runoff in watershed models is generally discussed controversially (Garen and Moore 2005). Gassman et al. (2007) point out that modifying the SCS-CN method or integrating more complex methods for the estimation of surface runoff in SWAT could improve model predictions. However, because it is relatively easy to parameterize, the SCS-CN method is still the method of choice in SWAT and a number of other watershed models. In watersheds like the Xiangxi Catchment, the use of more complex methods could lead to higher model error as the available data does not facilitate their parameterization. Shi et al. (2009) found out from field experiments in the Three Gorges Region, that reducing the initial abstraction ratio in the SCS-CN method can substantially improve runoff predictions.

The model calculates sediment yield in the HRUs based on the MUSLE. Sediment yields from all HRUs within a subbasin are summed and added to the main reach. Sediment delivery ratios are accounted for by a factor in the equation that was determined using data for 18 watersheds in the southern United States and is thus not necessarily valid for watersheds in different eco-regions. Additionally, FitzHugh and Mackay (2000) show that in the MUSLE there is a non-linear relationship between sediment and HRU area and that sediment yield varies proportionally with the HRU area raised to the 1.12 power. They point out, that the influence of the MUSLE soil erodibility (K), cover and management (C), support practice (P), topographic (LS) and coarse fragment (CFRG) factors is only secondary compared to the influence of the HRU area. Even though the conclusions drawn by FitzHugh and Mackay (2000) are generally supported by this study, results have demonstrated that the MUSLE K, C, P, LS and CFRG factors add further variability and thus further uncertainty to the sediment yield predictions in the Xiangxi Catchment.

Not all of the MUSLE factors could be adequately parameterized yet. For some factors, e.g. the C factor for forest, default parameter values from the SWAT databases had to be used, even though these were mostly developed to reflect North American conditions. Shen et al. (2011) point out that in the future the SWAT databases will have to be adapted to Chinese conditions. Ongley et al. (2010) question the transferability of SWAT databases to Chinese conditions as well, especially in agriculturally dominated watersheds, because only few Chinese crops are represented in the crop database and it is difficult to adequately consider the impacts of terraced agriculturally used slopes and rice paddies on runoff processes. While rice paddies occupy only marginal fractions of the Xiangxi Catchment, terraces are a prominent feature in the watershed. Schönbrodt-Stitt et al. (2012) have found a distinct variability of the P factor depending on the condition of terraces in the Xiangxi Catchment, which should ideally be reflected by the SWAT parameterization. The C factor values for orange orchards and cropland were taken from Shi et al. (2004) and can therefore generally be assumed to be suitable for the Three Gorges Region. However, as the cover and management factor is updated daily as a function of biomass, residue on the soil surface and the minimum C factor for the plant, inadequate biomass simulations can impact MUSLE sediment yield predictions. Also, the degree to which the C factor used for orange orchards in this study is representative is difficult to specify because of the varying growth stages of orange orchards in the Xiangxi Catchment. Lu and Higgitt (2001) point out that the cultivation of the steep and dissected terrain in the Three Gorges Region is generally beyond the parameter ranges of the USLE, which the MUSLE is based on.

The topographic factor LS is a combination of the slope length and the slope gradient factors. While an individual slope gradient is calculated by the ArcSWAT interface (Olivera et al. 2006) used in this study, the slope length was assumed to be constant. According to Hickey et al. (1994), of all USLE parameters, slope length is most difficult to calculate. Field measurements usually provide the best estimates of slope length but are rarely available for large watersheds. Therefore, it is common practice to use a regional estimate and thus treat slope length as a constant (Hickey 2000). However, this can lead to unrealistic slope length values. A number of methods are available to estimate the LS factor based on DEM data (Liu et al. 2011). Two common methods were developed by Desmet and Govers (1996) and Hickey et al. (1994). Kim et al. (2009) developed a GIS patch for the calculation of slope length specifically for SWAT applications and successfully applied this to a watershed in South Korea.

The quality of observed data is considered to be a crucial factor influencing model performance (Legesse et al. 2003). The observed data used for calibrating the sediment loads at Xingshan Gauge pose a large problem, because the exact technique and timing of the sediment sampling is not known (T. Jiang, personal communication, 2010). It is impossible to verify whether observed sediment peaks might be underestimated because short-term events were not captured by the sampling or whether they might be overestimated, because high loads measured during short-term events are extrapolated to whole days. This problem was also discussed by Benaman et al. (2005). Additionally, measurement errors might have occurred because of the choice of an unrepresentative sampling location or during laboratory analyses. Therefore, it is very difficult to decide how much importance should be attached to exactly simulating monthly sediment loads. Instead, it might be better to focus on a good simulation of average yearly loads, even though some accuracy of information is lost when using yearly instead of monthly data. The fact that observed data is only available for one gauge in the Xiangxi Catchment hampers the estimation of the model performance regarding the spatial variability of both hydrological and sediment-related processes within the watershed.

In future studies, model error can be reduced by improving the database and the model parameterization for the Xiangxi Catchment and by modifying selected SWAT databases and algorithms to better represent the characteristics of Chinese watersheds. However, even with very accurate input data and adequate model structure, there will always remain some uncertainty in model output. Abbaspour (2007) distinguishes four different types of model structure uncertainty, which he attributes to simplifications in the conceptual model, processes occurring in the watershed but not included in the model, processes that are included in the model but unknown to the modeler, and processes unknown to the modeler and not included in the model either. In the Xiangxi Catchment, a few processes occur that are difficult or impossible to consider in the model. Among these are landslides, sediment dredging activities and a large number of small hydropower plants.

Landslides have always occurred in the Three Gorges Region, but have been increasingly observed since the Three Gorges Dam was closed, because the stability of slopes is reduced by the fluctuating water level in the reservoir (Liu et al. 2004; He et al. 2008; Ehret et al. 2010). Landslides influence streamflow and sediment loads by adding tremendous amounts of soil to the river within a time frame of seconds or minutes. Sediment dredging is practiced in nearly all rivers within the Xiangxi Catchment during the dry season in winter, when it is possible to drive in the river channel with excavating machines and trucks. It influences sediment loads by locally swirling up sediment from the riverbed and impacts streamflow by substantially altering the river morphology. In the Xiangxi Catchment, there are more than 47 small hydropower plants (Fu et al. 2008), which divert the water from the river channel to pipes that run through the mountains. Because they have a lower gradient, the pipes are located on a higher elevation than the riverbed when they reappear above ground after covering a distance of a few kilometers. From there, an almost vertical pipe channels the water downhill to a power station and then back to the river. The small hydropower plants in the Xiangxi Catchment impact streamflow especially during low-flow periods, when all discharge is diverted and the riverbed between the inlet and the outlet of a hydropower plant completely dries up. Additionally, the two small dams located on Gufu River, which were put into operation in 1999 and 2004 and which influence the streamflow in Gufu River and thereby at Xingshan Gauge considerably, are difficult to integrate in the model as it was not possible to obtain detailed information about dam operations, e.g. the timing and amount of water release.

In recent years, automatic calibration procedures have been developed and become very popular in the field of hydrological modeling. An important advantage of auto-calibration is the possibility to estimate probability bands, which specify the range of possible model predictions from a given parameter set. Also, it avoids uncertainty introduced by the extent of experience and knowledge of the modeler (Abbaspour 2007). For SWAT, the program SWAT-CUP (Abbaspour 2007) provides a convenient interface for applying different auto-calibration techniques. However, auto-calibration results for the Xiangxi Catchment were not satisfactory. All available auto-calibration procedures rely on the definition of an objective function, e.g. NSE or R^2, as a measure of model performance. Calibration then aims at optimizing model performance as indicated by the chosen objective function. This often results in a strong focus on streamflow peaks, which are optimized at the expense of low-flow periods. Also, when observed data is only available for streamflow, it can lead to unrealistic simulations of the proportions of different water balance and flow components. Therefore, manual calibration was chosen over the use of an auto-calibration procedure in this study. However, in the future, the manual calibration of SWAT for the Xiangxi Catchment can be fine-tuned using an auto-calibration technique.

6.3 The choice of model

In light of the relatively large error in the model output for the Xiangxi Catchment the question arises, whether SWAT represents an adequate choice of model or not. Land use change studies in data-scarce regions generally involve the challenge of finding a balance between an adequate representation of crucial processes in a model and its data requirements. Empirical models like the USLE are still used because of their ease of application and low data requirements (Kliment et al. 2008). However, the reliability of results has to be verified carefully when empirical models are applied outside the range of the original experimental conditions (Amore et al. 2004). Also, they are not able to simulate physical processes in a watershed. In contrast, physically based models provide detailed simulations of processes, but they require a large amount of data and are usually applied to small watersheds with areas ranging between 10 and 100 km^2 (Kliment et al. 2008).

Conceptual models represent a compromise between these two model types by combining empirically derived algorithms with physically based ones (Borah and Bera 2003). Of all conceptual models available SWAT is the one that has been most extensively used and tested all over the world. A few authors have compared AnnAGNPS (Bingner et al. 2007) and SWAT model results, as both of these models are open source, conceptual models. Kliment et al. (2008) compared the performance of SWAT and AnnAGNPS in a watershed in Czech Republic and found SWAT to be more suitable for continuous simulations of streamflow and sediment loads. Parajuli et al. (2009) concluded from a model comparison in a watershed in Kansas that SWAT and AnnAGNPS performed equally well with regard to streamflow and sediment predictions. However, SWAT was able to provide considerably better phosphorus predictions. Shen et al. (2009) applied SWAT and the physically based erosion model WEPP (Flanagan and Nearing 1995) in the Zhangjiachong Catchment in the Three Gorges Region. They found that WEPP outperformed SWAT with regard to the simulation of sediment yields and suggest to replace the MUSLE with the algorithms used by WEPP in order to combine the strengths of both models for simulating sediment yield in small watersheds. However, because of the size of the Xiangxi Catchment this is not applicable for this study. Shi et al. (2011) used the Xinanjiang model (XAJ; Zhao et al. 1980) to simulate streamflow in the Xixian Watershed in China and compared results to SWAT predictions. Both models performed equally well, but the authors concluded that because of its ability to simulate water quantity and quality simultaneously, SWAT is more suitable as a tool for establishing sustainable water resources management in watersheds dominated by agriculture (Shi et al. 2011).

The objective of the Yangtze-GEO Project was to develop and test a methodology that can be transferred to other areas or watersheds, which are impacted by large dam projects. For this purpose, the use of freely available models is advantageous. SWAT is an open-source model, so any user can implement changes to the source code if desired. Also, it is accompanied by an elaborate documentation, which gives a detailed description of all model algorithms, parameters and input/output files. Another advantage of SWAT is the ArcSWAT interface (Olivera et al. 2006), which facilitates the model setup procedure as well as the pre- and post-processing of spatial data (Romanowicz et al. 2005).

Among the numerous hydrologic and water quality models that have been developed in recent years, SWAT is one of the most suitable models for simulating water and sediment yields under land use and management scenarios (Behera and Panda 2006). It has been successfully applied to watersheds all over the world, not only for hydrological simulations, but also for the assessment of sediment and nutrient transport in watersheds (Arnold and Fohrer 2005; Gassman et al. 2007). SWAT simulations in the Xiangxi Catchment yielded promising results, which demonstrate the general applicability and suitability of the model for achieving the objectives of both the Yangtze-GEO project and this dissertation.

6.4 Implications of results for land use planning in the Xiangxi Catchment

The results of this study indicate a strong need for sustainable development and management of land use in the Xiangxi Catchment. They show that cultivated sloping lands are the main contributors to soil loss and sediment yields. In spite of the uncertainties associated with the model output, the results of the land use scenario simulations are helpful for developing a sustainable watershed management plan. They give an idea about the general reaction of hydrological and sediment related processes to possible future land use changes. As all scenarios for a watershed are subject to the same input data uncertainty, it can be assumed that differences in scenario results can in fact be attributed to the applied scenario changes (Hessel et al. 2003).

Contrary to expectations, land use change in the Xiangxi Catchment between 1987 and 2007 has been characterized by an increase of forested areas. The effects on the proportions of evapotranspiration and water yield observed in this study are consistent with the findings of other authors (e.g. Bosch and Hewlett 1982; Sahin and Hall 1996). According to the model simulations, the past changes in land use led to a slight decrease of streamflow peaks and an increase in base flow, especially between 1987 and 1999. Groundwater flow has increased while the faster flow components have decreased. Simulation results demonstrate that soil loss and sediment loads have decreased between 1987 and 2007 in accordance with the increase in forested area and the decrease of surface runoff. However, an increasing occurrence of algae blooms, especially in the backwater areas of Yangtze River tributaries (Ye et al. 2006, 2007, 2009), indicates that under the modified conditions in the Three Gorges Reservoir with reduced flow velocities and prolonged residence times, the current sediment and nutrient inputs are still critical.

The Ministry of Water Resources of China (1997) suggested a soil loss tolerance value of 5 t ha^{-1} a^{-1} (Shi et al. 2004; Wang et al. 2010). For economic reasons, the Rural Water Conservancy and Soil Conservation Bureau of the Changjiang River Water Resources Commission (RWCSCB 1998) increased this value to 10 t ha^{-1} a^{-1} (Shi et al. 2004b). According to the simulation results for 2007, both thresholds are exceeded by a large fraction of cropland and also by a considerable fraction of orange orchards. Simulation results have demonstrated that a further afforestation of cropland would effectively reduce sediment inputs. However, this is not considered to be feasible as long as the livelihood of a large number of people in the Xiangxi Catchment depends on agriculture. Scenario simulations have also indicated that the conversion of forest to cropland or orange orchards would critically increase sediment yields from the Xiangxi Catchment. The advantage of orange orchards over cropland with regard to soil cover and protection from erosion remains difficult to estimate and verify because of the varying growth stages of orange orchards occurring in the watershed.

The amount of sediment inputs does not necessarily equal the soil loss from cropland and orange orchards, because parts of the eroded material can be deposited and stored during transport to the river (Lu and Higgitt 2000). Therefore, it is important to analyze sediment transport pathways and sediment delivery ratios. In this context, the proximity of croplands and orange orchards to the rivers and the Three Gorges Reservoir is considered an important factor: the closer an agriculturally used area is to the river or the reservoir, the more likely it is that the eroded material will actually reach it and contribute to its sediment load. It is crucial to consider the proximity of cultivated land to surface waters when analyzing the simulation results, especially as sediment delivery ratios are not optimally taken into account in SWAT yet.

A number of authors discuss the effects of land use changes on model parameters that are not strictly related to land use. Especially changes in soil hydraulic properties and strategies for their estimation have been investigated in recent years (Chaplot et al. 2004; Heuvelmans et al. 2004; Huisman et al. 2004; Breuer et al. 2006; Bormann et al. 2007). While most of these authors found changes in soil properties to be a significant factor influencing model results, Breuer et al. (2006) concluded from their study that they are only of minor importance with regard to the hydrological effects of land use changes. Extensive sensitivity analyses would be necessary to examine the role of changes in soil properties in the Xiangxi Catchment. However, this would require more reliable and spatially refined information on the soil properties than currently available for this watershed and thus remains a possible topic for future research.

The results of the scenario simulations are helpful for developing a sustainable watershed management plan. They give an idea about the order of magnitude of the reaction of the water and sediment related processes to possible future land use changes. However, they do not include alterations of crop rotations or tillage practices or the implementation of soil conservation practices. Therefore, they do not support the actual formulation of watershed management plans yet.

Various studies have estimated the efficiency of different soil conservation measures, e.g. terraces and contour hedgerows, which are considered to be the two main soil conservation measures in the Three Gorges Region (Shen et al. 2010b). The latter have been introduced to the region in the 1980s and have proven to be an effective means of reducing surface runoff and sediment yields when planted at a distance of 3 to 6 m (Bu et al. 2008; Ng et al 2008; Shen et al. 2010b). Terracing has been practiced in mountainous areas in China for many centuries (Shen et al. 2010b). Terraces can effectively reduce surface runoff and soil loss (Meng et al. 2001), but require high inputs of labour and capital. Shi et al. (2004) state that on very steep slopes, the spacing between terraces becomes too small and thereby the terraces become too expensive to construct. However, according to Lu et al. (2004), building and maintenance of terraces mainly takes place during fallowness of the cropland and thereby contributes to the enhancement of rural labor utilization. The condition of terraces in the Xiangxi Catchment is highly dependent on the farmer's experience in terracing (S. Schönbrodt-Stitt, personal communication, 2011). While the terraces of farmers who have always practiced agriculture on steeply sloping land are usually very well maintained, the farmers who were recently relocated from the valley bottoms to steep slopes often lack the knowledge to properly build and maintain terraces. Terraces are indirectly considered in this study by adapting the P factor of the MUSLE equation, but the condition of the terraces, which has shown to be a critical factor determining their efficiency in preventing soil loss (S. Schönbrodt-Stitt, personal communication, 2011), could not be taken into account yet.

Wang et al. (2010) recommend the afforestation of very steep slopes, while they propose the adoption of improved soil conservation measures on moderately steep slopes. Even though the effects of management and soil conservation practices has not been investigated in this study, the results can support the identification of spatial hotspots of soil erosion and identify those areas of the watershed where a change of management practices would not be sufficient and afforestation is the only effective means of reducing soil erosion. Long et al. (2006) suggest to distinguish the soil conservation measures (e.g. terracing, contour tillage and intercropping) depending on the feasibility of improving the sloping farmlands. This is an important topic, which should be addressed by further research in the Xiangxi Catchment and the entire Three Gorges Region. So far, studies using SWAT to assess the effect of Best Management Practices have been mostly conducted in the US (e.g. Vaché et al. 2002; Santhi et al. 2006; Bracmort et al. 2006; Arabi et al. 2008). In China, non-point source pollution and approaches to its mitigation have only recently become a major focus of research (Shen et al. 2011). Liu et al. (2013) have simulated the effects of Best Management Practices on agricultural non-point source pollution in the Xiangxi Catchment. However, both their basic model calibration and their implementation of Best Management Practices in the model is highly questionable, so there remains a strong need for further research in the Xiangxi Catchment.

6.5 Conclusions and outlook

The research conducted in the past four years in the context of the Yangtze-GEO project and this dissertation provides an initial assessment of the current situation and a first estimate of the impacts of land use change in the Xiangxi Catchment on water resources. A basic database for future research was created and the most important sources of uncertainty were identified. Therefore, the groundwork for further research in the Xiangxi Catchment and in the entire Three Gorges Region has been laid successfully.

Results indicate a strong need for sustainable development and management of land use in the Xiangxi Catchment. They demonstrate that in spite of a reduction of agriculturally used areas in the past, sediment inputs to rivers are still high. Cultivated sloping land was identified as the major contributor to soil loss and sediment yields. Because of nutrients attached to the soil particles, the sediment inputs entail a high risk of eutrophication, especially since the formation of backwater areas in the Yangtze River tributaries has reduced the flow velocities and accordingly increased the residence time of water considerably. Sustainable watershed management is crucial for ecological preservation and for safeguarding the future usability of water resources in the Three Gorges Region. Possible conflicts between the interests of environment and local population have been pointed out in this study based on the simulation of land use scenarios.

The results of this dissertation reveal a lack of empirical data to parameterize and verify the model. They also indicate the need to revise knowledge of basic processes and their mathematical representation in order to better account for the specific characteristics of Chinese watersheds. The application of hydrological models like SWAT to Chinese watersheds in order to improve their capability to represent Chinese conditions is an important prerequisite for simulating land use and management scenarios and identifying suitable strategies for non-point source pollution control, especially in the highly dynamic ecosystem of the Three Gorges Region. The assessment of the complex interactions of land use and water quantity and quality as influenced by the construction of the Three Gorges Dam and the reservoir impoundment will require many more years of research. By engaging in a second project phase, the Yangtze-GEO project will contribute to ongoing research and scientific cooperation for promoting a sustainable development of natural resources in the Three Gorges Region. Future research has to respond to the challenges that were identified in the past four years. Primarily, there is a strong need to reduce uncertainty in the SWAT model simulations.

Firstly, the influence of the subbasin delineation should be tested to evaluate its effect on streamflow and sediment yield predictions. A higher number of subbasins than delineated in this study may be advantageous, as it introduces a higher degree of spatial identifiability and geographical linkage. Secondly, it is crucial to obtain spatial input data with a higher resolution. Many studies have stressed the relevance of the spatial resolution of DEM, soil map and land use map. The Yangtze-GEO project focuses on the effects of land use change in the Three Gorges Region on natural resources. Accordingly, a high resolution land use map is crucial for achieving the project objectives. The land use maps used for this dissertation have a resolution of 30 x 30 m. This has been shown to be insufficient for capturing the small-scale variations of agricultural land use in the Xiangxi Catchment. A land use map with a higher resolution is indispensable for simulating the diverse pattern of crops in the watershed and integrating more detailed and realistic management schemes in the model. These are an important prerequisite for the identification of Critical Source Areas and the simulation of Best Management Practices, which was not supported by the available data so far. Another important topic is the integration of terraces in the model. Currently, the terraces are indirectly accounted for by adapting the P factor in the MUSLE. Simulations can be improved by introducing more spatial variability to the P factor parameterization as a function of terrace condition, which has been shown to be a key factor governing the protection from soil erosion provided by the terraces in the Xiangxi Catchment.

In the future, as much additional observed data as possible should be obtained from Chinese project partners or authorities. Also, ways have to be found to improve model verification by using the available data as efficiently as possible. Additional techniques for analyzing the data to extract the maximum amount of information possible should be developed and tested. This may include detailed analysis of temporal variations of model output, e.g. a comparison of different seasons or wet, dry and average years. Field work should continue to be an integral part of research in the Three Gorges Region as it increases the knowledge of the specific characteristics of watersheds like the Xiangxi Catchment. Also it is crucial for obtaining important and useful data for model parameterization and verification. Detailed literature research including Chinese literature resources should be conducted to complement field work and ensure the utilization of all available information. Both field work and literature research can help to improve the representation of Chinese conditions in the SWAT algorithms and model databases, for example with regard to the specific characteristics of Chinese crops and soil types, and promote a realistic and application-oriented evaluation of model results. Finally, even though the Xiangxi Catchment is considered to be representative of the eastern part of the Three Gorges Region, the methodology should be applied and tested in neighboring watersheds to test and improve its transferability.

No matter how much information and data are available for a watershed, there will always be a certain amount of error and uncertainty in model results. After all, models are mathematical representations of an extremely heterogenous reality that is subject to unpredictable natural variability. However, estimating the impacts of human interferences with nature, for example the Three Gorges Project, is crucial to sustain adequate living conditions for all inhabitants of this planet. All research in the field of natural sciences should be accompanied by a detailed assessment and discussion of uncertainties associated with the obtained results.

As stated by Rosgen (1994), "one axiom associated with rivers is that what initially appears complex is even more so upon further investigation". This is certainly true for the Xiangxi Catchment. Answering one question tends to bring up a number of new questions, all of which are worth being investigated. Hopefully, this study was able to lay the groundwork for answering as many of those questions as possible in the future and to contribute to hydrological research in the Three Gorges Region, which is crucial for safeguarding the natural resources in this unique ecosystem.

Chapter 7

References

Abbaspour, K.C. 2007. User manual for SWAT-CUP, SWAT calibration and uncertainty analysis programs. Eawag, Dübendorf, Switzerland.

Abbaspour, K.C., J. Yang, I. Maximov, R. Siber, K. Bogner, J. Mieleitner, J. Zobrist and R. Srinivasan. 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. Hydrol. 333: 413–430.

Abrams, M.M. and W.M. Jarrell. 1995. Soil phosphorus as a potential non-point source for elevated stream phosphorus levels. J. Environ. Qual. 24: 132–138.

Ahl, R.S., S.W. Woods and H.R. Zuuring. 2008. Hydrologic calibration and validation of SWAT in a snow-dominated Rock Mountain Watershed, Montana, U.S.A. JAWRA 44(4): 1–21.

Aitken, A.P. 1973. Assessing systematic errors in rainfall-runoff models, J. Hydrol. 20: 121–136.

Amore, E., C. Modica, M.A. Nearing and V. C. Santoro. 2004. Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. J. Hydrol. 293: 100–114.

Arabi, M., R.S. Govindaraju, M.H. Hantush, and B.A. Engel. 2006. Role of watershed subdivision on modeling the effectiveness of Best Management Practices with SWAT. JAWRA 42(2): 513–528.

Arabi, M., R.S. Govindaraju, B. Engel and M. Hantush. 2007. Multiobjective sensitivity analysis of sediment and nitrogen processes with a watershed model. Water Resour. Res. 43. doi:10.1029/2006WR005463.

Arabi, M., J.R. Frankenberger, B.A. Engel and J.G. Arnold. 2008. Representation of agricultural conservation practices with SWAT. Hydrol. Process. 22: 3042–3055.

Arnold, J.G., J.R. Williams and D.R. Maidment. 1995. Continuous-time water and sediment routing model for large basins. J. Hydraulic Eng. 121(2): 171–183.

Arnold, J.G., R. Srinivasan, R.S. Muttiah and J.R. Williams. 1998. Large area hydrologic modeling and assessment – part I: model development. JAWRA 34(1): 73–89.

Arnold, J.G. and P.M. Allen. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. JAWRA 35(2): 411–424.

Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol. Process. 19: 563–572.

Arnold, J.G., P.M. Allen, M. Volk, J.R. Williams and D.D. Bosch. 2010. Assessment of Different Representations of Spatial Variability on SWAT Model Performance. Trans. ASABE 53(5): 1433–1443.

Bahel, V., H. Bakhsh and R. Srinivasan. 1987. A correlation for estimation of global solar radiation. Energy 12(2): 131–135.

Behera, S. and R.K. Panda. 2006. Evaluation of management alternatives for an agricultural watershed in a sub-humid subtropical region using a physical process based model. Agr. Ecosyst. Environ. 113: 62–72.

Bekele, E.G. and J.W. Nicklow. 2007. Multi-objective automatic calibration of SWAT using NSGA-II. J. Hydrol. 341: 165–176.

Benaman, J., C.A. Shoemaker and D.A. Haith. 2005. Calibration and Validation of Soil and Water Assessment Tool on an Agricultural Watershed in Upstate New York. J. Hydrol. Eng. 10(5): 363–374.

Bennett, M.T. 2008. China's sloping land conversion program: Institutional innovation or business as usual? Ecol. Econ. 65: 699–711.

Beven, K.J. 1989. Changing Ideas in Hydrology: The Case of Physically-Based Models. J. Hydrol. 105: 157–172.

Bieger, K., G. Hörmann and N. Fohrer. 2012. Simulation of streamflow and sediment with the SWAT model in a data scarce catchment in the Three Gorges Region, China. J. Environ. Qual. doi: 10.2134/jeq2011.0383.

Bingner, R.L., J. Garbrecht, J.G. Arnold and R. Srinivasan. 1997. Effect of Watershed Subdivision on Simulation Runoff and Fine Sediment Yield. Trans. ASAE 40(5): 1329–1335.

Bingner, R.L., F.D. Theurer and Y. Yongping. 2007. AnnAGNPS technical processes documentation, Version 4.0. USDA-ARS, National Sedimentation Laboratory, Oxford, MS.

Borah, D.K. and M. Bera. 2003. Watershed-Scale Hydrologic and Nonpoint-Source Pollution Models: Review of Mathematical Bases. Trans. ASAE 46(6): 1553–1566.

Bormann, H., L. Breuer, T. Gräff, J.A. Huisman. 2007. Analysing the effects of soil properties changes associated with land use changes on the simulated water balance: A comparison of three hydrological catchment models for scenario analysis. Ecol. Model. 209: 29–40.

Bosch, D.D., J.G. Arnold, M. Volk and P.M. Allen. 2010. Simulation of a Low-Gradient Coastal Plain Watershed Using the SWAT Landscape Model. Trans. ASABE 53(5): 1445–1456.

Bosch, J.M. and J.D. Hewlett. 1982. A Review of Catchment Experiments to determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration. J. Hydrol. 55: 3–23.

Bracmort, K.S., M. Arabi, J.R. Frankenberger, B.A. Engel and J.G. Arnold. 2006. Modeling Long-Term Water Quality Impact of Structural BMPs. Trans. ASABE 49(2): 367–374.

Breuer, L., J. Huisman and H.-G. Frede. 2006. Monte Carlo assessment of uncertainty in the simulated hydrological response to land use change. Environ. Model. Assess. 11: 209–218.

Bu, C.F., Q.G. Cai, S.L. Ng, K.C. Chau and S.W. Ding. 2008. Effects of hedgerows on sediment erosion in Three Gorges Dam Area, China. Int. J. Sediment Res. 23: 119–129.

Bultot, F., G.L. Dupriez and D. Gellens. 1990. Simulation of land use changes and impacts on the water balance – a case study for Belgium. J. Hydrol. 114: 327–348.

Busteed, P.R., D.E. Storm, M.J. White and S.H. Stoodley. 2009. Using SWAT to Target Critical Source Sediment and Phosphorus Areas in the Wister Lake Basin, USA. Am. J. Environ. Sci. 5(2): 156–163.

Cai, Q.G., H. Wang, D. Curtin and Y. Zhu. 2005. Evaluation of the EUROSEM model with single event data on Steeplands in the Three Gorges Reservoir Areas, China. Catena 59: 19–33.

Cao, W., W.B. Bowden, T. Davie and A. Fenemor. 2006. Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrol. Process. 20: 1057–1073.

Cao, W., W.B. Bowden, T. Davie and A. Fenemor. 2009. Modelling Impacts of Land Cover Change on Critical Water Resources in the Motueka River Catchment, New Zealand. Water Resour. Manag. 23: 137–151.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley and V.H. Smith. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecol. Appl. 8(3): 559–568.

Chaplot, V., A. Saleh, D.B. Jaynes and J. Arnold. 2004. Predicting water, sediment and NO3-N loads under scenarios of land-use and management practices in a flat watershed. Water Air Soil Poll. 154: 271–293.

Chaplot, V. 2005. Impact of DEM mesh size and soil map scale on SWAT runoff, sediment, and NO3-N loads predictions. J. Hydrol. 312: 207–222.

Chaplot, V., A. Saleh and D.B. Jaynes. 2005. Effect of the accuracy of spatial rainfall information on the modeling of water, sediment, and NO3–N loads at the watershed level. J. Hydrol. 312: 223–234.

Chaubey, I., A.S. Cotter, T.A. Costello and T.S. Soerens. 2005. Effect of DEM data resolution on SWAT output uncertainty. Hydrol. Process. 19: 621–628.

Chen, B.M. and X.P. Zhou. 2007. Explanation of Current Land Use Condition Classification for National Standard of the People's Republic of China. (In Chinese with English abstract.) J. Nat. Res. 22(6): 994–1003.

Chen, E. and D.S. Mackay. 2004. Effects of distribution-based parameter aggregation on a spatially distributed agricultural nonpoint source pollution model. J. Hydrol. 295: 211–224.

Chen, J., X. Li and M. Zhang. 2005. Simulating the impacts of climate variation and land-cover changes on basin hydrology: A case study of the Suomo basin. Science in China Ser. D Earth Sciences 48(9): 1501–1509.

Chen, M., J. Chen and F. Sun. 2008. Agricultural phosphorus flow and its environmental impacts in China. Sci. Total. Environ. 405: 140–152.

Chen, Y., Y. Xu and Y. Yin. 2009. Impacts of land use change scenarios on storm-runoff generation in Xitiaoxi basin, China. Quatern. Int. 208: 121–128.

Cheng, H., W. Ouyang, F. Hao, X. Ren and S. Yang. 2007. The non-point source pollution in livestock-breeding areas of the Heihe River basin in Yellow River. Stoch. Environ. Res. and Risk Assess 21: 213–221.

China Soil Scientific Database: http://www.soil.csdb.cn/, last access: 18 June 2010.

Chu, T.W., A. Shirmohammadi, H. Montas and A. Sadeghi. 2004. Evaluation of the SWAT model's Sediment and Nutrient Components in the Piedmont Physiographic Region of Maryland. Trans. ASAE 47(5): 1523–1538.

CIPM. 1988. Three Gorges Water Control Project Feasibility Study, vols. 1–11. CIPM, Canada.

Costa, M.H., A. Botta and J.A. Cardille. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J. Hydrol. 283: 206–217.

Cotter, A.S., I. Chaubey, T.A. Costello, T.S. Soerens and M.A. Nelson. 2003. Water quality model output uncertainty as affected by spatial resolution of input data. JAWRA 39(4): 977-986.

Dai, H., T. Zheng and D. Liu. 2010. Effects of Reservoir Impounding on Key Ecological Factors in the Three Gorges Region. Proc. Environ. Sci. 2: 15–24.

DeFries, R. and K.N. Eshleman. 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrol. Process. 18: 2183–2186

Desmet, P.J.J. and G. Govers. 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. J. Soil Water Conserv. 51: 427–433.

Di Luzio, M., J.G. Arnold and R. Srinivasan. 2005. Effect of GIS data quality on small watershed stream flow and sediment simulations. Hydrol. Process. 19: 629–650.

Earls, J. and B. Dixon. 2008. A Comparison of SWAT Model-Predicted Potential Evapotranspiration Using Real and Modeled Meteorological Data. Vadose Zone J. 7: 570–580.

Eckhardt, K. and J.G. Arnold. 2001. Automatic calibration of a distributed catchment model. J. Hydrol. 251: 103–109.

Eckhardt, K., L. Breuer and H.-G. Frede. 2003. Parameter uncertainty and the significance of simulated land use change effects. J. Hydrol. 273: 164–176.

Eckhardt, K., N. Fohrer and H.-G. Frede. 2005. Automatic model calibration, Hydrol. Process. 19: 651–658.

Ehret, D., J. Rohn, C. Dumperth, S. Eckstein, S. Ernstberger, K. Otte, R. Rudolph, J. Wiedenmann, X. Wei and B. Renneng. 2010. Frequency Ratio Analysis of Mass Movements in the Xiangxi Catchment, Three Gorges Reservoir Area, China. J. Earth Sci. 21(6): 824–834.

Fearnside, P.M. 1988. China's Three Gorges Dam: "Fatal" project or step toward modernization? World Dev. 16(5): 615–630.

Feaster, T.D., H.E. Golden, K.R. Odom, M.A. Lowery, P.A. Conrads and P.M. Bradley. 2010. Simulation of streamflow in the McTier Creek watershed, South Carolina. U.S. Geological Survey Scientific Investigations Report 2010-5202, U.S. Geological Survey, Reston, VA: 61pp.

Feng, S., Q. Hu and W. Qian. 2004. Quality control of daily meteorological data in China, 1951-2000: a new dataset. Int. J. Climatol. 24: 853–870.

FitzHugh, T.W. and D.S. Mackay. 2000. Impacts of Input Parameter Spatial Aggregation on an Agricultural Nonpoint Source Pollution Model. J. Hydrol. 236: 35–53.

Flanagan, D.C. and N.A. Nearing. 1995. USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory. West Lafayette, IN.

Fohrer, N., S. Haverkamp, K. Eckhardt and H.-G. Frede. 2001. Hydrologic Response to Land Use Changes on the Catchment Scale. Phys. Chem. Earth (B) 26(7-8): 577–582.

Fohrer, N., D. Möller and N. Steiner. 2002. An interdisciplinary modelling approach to evaluate the effects of land use change. Phys. Chem. Earth 27: 655–662.

Fohrer, N., S. Haverkamp and H.-G. Frede. 2005. Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas. Hydrol. Proc. 19: 659–672.

Fontaine, T.A., T.S. Cruickshank, J.G. Arnold and R.H. Hotchkiss. 2002. Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J. Hydrol. 262: 209–223.

Fu, X., T. Tang, W. Jiang, F. Li, N. Wu, S. Zhou and Q. Cai. 2008. Impacts of small hydropower plants on macroinvertebrate communities. Acta Ecologica Sinica 28(1): 45–52.

Gächter, R., S.M. Steingruber, M. Reinhardt and B. Wehrli. 2004. Nutrient transfer from soil to surface waters: Differences between nitrate and phosphate. Aquat. Sci. 66: 117–122.

Garen, D.C. and S. Moore. 2005. Curve Number Hydrology in Water Quality Modeling: Uses, Abuses, and Future Directions. JAWRA 41(2): 377–388.

Gassman, P.W., M.R. Reyes, C.H. Green and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. Trans. ASABE 50(4): 1211-1250.

Ghaffari, G., S. Keesstra, J. Ghodousi and H. Ahmadi. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. Hydrol. Process. 24: 892–903.

Giri, S., A.P. Nejadhashemi and S.A. Woznicki. 2012. Evaluation of targeting methods for implementation of best management practices in the Saginaw River Watershed. J. Environ. Manage. 103: 24–40.

Gong, Y., Z. Shen, Q. Hong, R. Liu and Q. Liao. 2011. Parameter uncertainty analysis in watershed total phosphorus modeling using the GLUE methodology. Agric. Ecosyst. Environ. 142: 246–255.

Green, C.H. and A. van Griensven. 2008. Autocalibration in hydrologic modeling: Using SWAT2005 in small-scale watersheds. Environ. Modell. Softw. 23: 422–434.

Green, W.H. and G.A. Ampt. 1911. Studies on soil physics, 1. The flow of air and water through soils. J. Agric. Sci. 4: 11–24.

Guo, H., Q. Hu and T. Jiang. 2008. Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake basin, China. J. Hydrol. 355: 106–122.

Guo, H., Q. Hu, Q. Zhang and S. Feng. 2012. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003-2008. J. Hydrol. 416-417: 19–27.

Guo, Z., X. Xiao, Y. Gan and Y. Zheng. 2003. Landscape planning for a rural ecosystem: case study of a resettlement area for residents from land submerged by the Three Gorges Reservoir, China. Landsc. Ecol. 18: 503–512.

Gupta, H.V., S. Sorooshian and P.O. Yapo. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration, J. Hydrol. Eng. 4(2): 135–143.

Hao, F., X. Zhang and Z. Yang. 2004. A distributed non-point source pollution model: calibration and validation in the Yellow River Basin. J. Environ. Sci. (Beijing, China) 16(4): 646–650.

Hargreaves, G.L., G.H. Hargreaves and J.P. Riley. 1985. Agricultural benefits for Senegal River Basin. J. Irrigation Drainage Eng. 111(2): 113-124.

Hartmann, H. and S. Becker. 2003. Critical Discussion of the Three Gorges Project's Consequences. J. Lake Sci. 15: 249–254.

Haverkamp, S., N. Fohrer and H.-G. Frede. 2005. Assessment of the effect of land use patterns on hydrologic landscape functions: a comprehensive GIS-based tool to minimize model uncertainty resulting from spatial aggregation. Hydrol. Process. 19: 715–727.

Haygarth, P.M., F.L. Wood, A.L. Heathwaite and P.J. Butler. 2005. Phosphorus dynamics observed through increasing scales in a nested headwater-to-river channel study. Sci. Total Environ. 344: 83–106

He, H., J. Zhou and W. Zhang. 2008. Modelling the impacts of environmental changes on hydrological regimes in the Hei River Watershed, China. Glob. Planet. Change 61: 175–193.

He, L., L. King and T. Jiang. 2003. On the land use in Three Gorges Reservoir area. J. Geogr. Sci. 13(4): 416–422.

Heathwaite, A.L. and P.J. Johnes. 1996. Contribution of Nitrogen Species and Phosphorus Fractions to Stream Water Quality in Agricultural Catchments. Hydrol. Process. 10: 971–983.

Heggelund, G. 2006. Resettlement Programmes and Environmental Capacity in the Three Gorges Dam Project. Dev. Change 37(1): 179–199.

Hessel, R., I. Messing, L. Chen, C. Ritsema and J. Stolte. 2003. Soil erosion simulations of land use scenarios for a small Loess Plateau catchment. Catena 54: 289–302.

Heuvelmans, G., B. Muys and J. Feyen. 2004. Evaluation of hydrological model parameter transferability for simulating the impact of land use on catchment hydrology. Phys. Chem. Earth 29: 739–747.

Hickey, R. 2000. Slope Angle and Slope Length Solutions for GIS. Cartography 29(1): 1–8.

Hickey, R., A. Smith and P. Jankowski. 1994. Slope length calculations from a DEM within ARC/INFO grid. Comput. Environ. Urban Syst. 18(5): 365–380.

Higgitt, D.L. and X.X. Lu. 1996. Patterns of sediment yield in the Upper Yangtze basin, China. IAHS Publ. 236: 205–214.

Higgitt, D.L. and X.X. Lu. 2001. Sediment delivery to the three gorges: 1. Catchment controls. Geomorphol. 41: 143–156.

Hörmann, G., N. Köplin, Q. Cai and N. Fohrer. 2009. Using a simple model as a tool to parameterise the SWAT model of the Xinagxi river in China, Quatern. Int. 208: 116–120.

Huang, M., J. Gallichand, Z. Wang and M. Goulet. 2006. A modification to the Soil Conservation Service curve number method for steep slopes in the Loess Plateau of China. Hydrol. Process. 20: 579–589.

Huang, S., C. Hesse, V. Krysanova and F. Hattermann. 2009a. From meso- to macro-scale dynamic water quality modelling for the assessment of land use change scenarios. Ecol. Model. 220: 2543–2558.

Huang, Z., B. Xue and Y. Pang. 2009b. Simulation on stream flow and nutrient loadings in Gucheng Lake, Low Yangtze River Basin, based on SWAT model. Quatern. Int. 208: 109–115.

Hubacek, K. and L. Sun. 2001. A scenario analysis of China's land use and land cover change: incorporating biophysical information into input-output modeling. Struct. Change Econ. Dyn. 12: 367–397.

Huisman, J.A., L. Breuer and H.-G. Frede. 2004. Sensitivity of simulated hydrological fluxes towards changes in soil properties in response to land use change. Phys. Chem. Earth 29: 749–758.

Inamdar, S. and A. Naumov. 2006. Assessment of Sediment Yields for a Mixed-landuse Great Lakes Watershed: Lessons from Field Measurements and Modeling. J. Great Lakes Res. 32: 471–488.

Jarvis, A., H.I. Reuter, A. Nelson and E. Guevara. 2008. Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database (http://srtm.csi.cgiar.org).

Jayakrishnan, R., R. Srinivasan, C. Santhi and J.G. Arnold. 2005. Advances in the application of the SWAT model for water resources management. Hydrol. Process. 19: 749–762.

Jha, M., P.W. Gassman, S. Secchi, R. Gu and J. Arnold. 2004. Effect of watershed subdivision on SWAT flow, sediment, and nutrient predictions. JAWRA 40(3): 811–825.

Jha, M.K., K.E. Schilling, P.W. Gassman and C.F. Wolter. 2010. Targeting land-use change for nitrate-nitrogen load reductions in an agricultural watershed. J. Soil Water Conserv. 65(6): 342–352.

Jim, C.Y. and F.Y. Yang. 2006. Local Responses to Inundation and De-Farming in the Reservoir Region of the Three Gorges Project (China). Environ. Manage. 38: 618–637.

Johnes, P.J. and R.A. Hodgkinson. 1998. Phosphorus loss from agricultural catchments: pathways and implications for management. Soil Use Manage. 14: 175–185.

Kalin, L., and M.M. Hantush. 2003. Evaluation of Sediment Transport Models and Comparative Application of Two Watershed Models. Report no. EP A/600/R-03/139. National Risk Management Research Laboratory, Cincinnati, OH.

Kannan, N., S.M. White, F. Worrall and M.J. Whelan. 2007a. Sensitivity analysis and identification of the best evapotranspiration and runoff options for hydrological modelling in SWAT-2000. J. Hydrol. 332: 456–466.

Kannan, N., S.M. White, F. Worrall and M.J. Whelan. 2007b. Hydrological modelling of a small catchment using SWAT-2000 – Ensuring correct flow partitioning for contaminant modeling. J. Hydrol. 334: 64–72.

Kepner, W.G., D.J. Sammens, S.D. Bassett, D.A. Mouat and D.C. Goodrich. 2004. Scenario analysis for the San Pedro River, analyzing hydrological consequences of a future environment. Environ. Monit. Assess. 94: 115–127.

Kim, J.-G., Y. Park, D. Yoo, N.-W. Kim, B.A. Engel, S.-J. Kim, K.-S. Kim and K.J. Lim. 2009. Development of a SWAT patch for better estimation of sediment yield in steep sloping watersheds. JAWRA 45(4): 963–972.

King, L., M. Gemmer and M. Metzler. 2002. Das Drei-Schluchten-Projekt am Yangtze. Gießener Forschergruppe untersucht Auswirkungen des weltgrößten Staudammprojektes. Spiegel der Forschung 19(1): 38–45.

Kirsch, K., A. Kirsch and J.G. Arnold. 2002. Predicting Sediment and Phosphorus Loads in the Rock River Basin Using SWAT. Trans. ASAE 45(6): 1757–1769.

Kliment, Z., J. Kadlec and J. Langhammer. 2008. Evaluation of suspended load changes using AnnAGNPS and SWAT semi-empirical erosion models. Catena 73: 286–299.

Klöcking, B. and U. Haberlandt. 2002. Impact of land use changes on water dynamics - a case study in temperate meso and macroscale river basins. Phys. Chem. Earth 27: 619–629.

Lai, G., G. Yu and F. Gui. 2006. Preliminary study on assessment of nutrient transport in the Taihu Basin based on SWAT modeling. Science in China: Series D Earth Sciences 49(I): 135–145.

Lal, R. 2001. Soil Degradation by Erosion. Land Degrad. Develop. 12: 519–539.

Lam, Q.D., B. Schmalz and N. Fohrer. 2012. Assessing the spatial and temporal variations of water quality in lowland areas, Northern Germany. J. Hydrol. 438-439: 137–147.

Legates, D.R. and G.J. McCabe. 1999. Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resour. Res. 35(1): 233–241.

Legesse, D., C. Vallet-Coulomb and F. Gasse. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. J. Hydrol. 275: 67–85.

Leh, M., S. Bajwa and I. Chaubey. 2011. Impact of Land Use Change on Erosion Risk: An Integrated Remote Sensing, Geographic Information System and Modeling Methodology. Land Degrad. Dev. doi: 10.1002/ldr.1137

Lenhart, T., N. Fohrer and H.-G. Frede. 2003. Effects of land use changes on the nutrient balance in mesoscale catchments. Phys. Chem. Earth 28: 1301–1309.

Lenhart, T., A. Van Rompaey, A. Steegen, N. Fohrer, H.-G. Frede and G. Govers. 2005. Considering spatial distribution and deposition of sediment in lumped and semi-distributed models. Hydrol. Process. 19, 785–794.

Lenton, R. and M. Muller. 2009. Integrated water resources management in practice: better water management for development. Earthscan, London, Sterling, VA.

Li, F., L. Ye, R. Liu, M. Cao and Q. Cai. 2008. Dynamics of main nutrient input to Xiangxi Bay of the Three-Gorges Reservoir. Acta Ecologica Sinica 28(5): 2073–2079.

Li, M., W. Yao, Z. Li, P. Liu and Z. Shen. 2010. Effects of landforms on the erosion rate in a small watershed by the 137Cs tracing method. J. Environ. Radioact. 101: 380–384.

Li, Q., M. Yu, G. Lu, T. Cai, X. Bai and Z. Xia. 2011. Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China. J. Hydrol. 403(3-4): 224–233.

Lijklema, L., A.A. Koelmans and R. Portielje. 1993. Water quality impacts of sediment pollution and the role of early diagenesis. Water Sci. Technol. 28: 123–132.

Lin, Y.P., N.M. Hong, P.J. Wu, C.F. Wu and P.H. Verburg. 2007. Impacts of land use change scenarios on hydrology and land use patterns in the Wu-Tu watershed in Northern Taiwan. Landsc. Urban Plan. 80: 111–126.

Linsley, R.K., M.A. Kohler and J.L.H. Paulhus. 1958. Hydrology for engineers. McGraw-Hill, New York.

Liu, C. and D. Zuo. 1987. Environmental Issues of the Three Gorges Project, China. Regulated Rivers: Research & Management 1: 267–273.

Liu, H., J. Kiesel, G. Hörmann, N. Fohrer. 2011. Effects of DEM horizontal resolution and methods on calculating the slope length factor in gently rolling landscapes. Catena 87: 368–375.

Liu, J.G., P.J. Mason, N. Clerici, S. Chen, A. Davis, F. Miao, H. Deng and L. Liang. 2004. Landslide hazard assessment in the Three Gorges area of the Yangtze river using ASTER imagery: Zigui–Badong. Geomorphol. 61: 171–187.

Liu, R., P. Zhang, X. Wang, Y. Chen and Z. Shen. 2013. Assessment of effects of best management practices on agricultural non-point source pollution in Xiangxi River watershed. Agric. Water Manage. 117: 9–18.

Liu, S.M., J. Zhang, H.T. Chen, Y. Wu, H. Xiong and Z.F. Zhang. 2003. Nutrients in the Changjiang and its tributaries. Biogeochemistry 62: 1–18.

Long, H.L., G.K. Heilig, J. Wang, X.B. Li, M. Luo, X.Q. Wu and M. Zhang. 2006. Land use and soil erosion in the upper reaches of the Yangtze River: some socio-economic considerations on China's Grain-for-Green Programme. Land Degrad. Dev. 17: 589–603.

Lu, C.H., M.K. van Ittersum and R. Rabbinge. 2004. A scenario exploration of strategic land use options for the Loess Plateau in northern China. Agric. Syst. 79: 145–170.

Lu, X.X. and D.L. Higgitt. 2000. Estimating erosion rates on sloping agricultural land in the Yangtze Three Gorges, China, from caesium-137 measurements. Catena 39: 33–51.

Lu, X.X. and D.L. Higgitt. 2001. Sediment delivery to the Three Gorges: 2: Local response. Geomorphol. 41: 157–169.

Luo, G., C. Yin, X. Chen, W. Xu and L. Lu. 2010. Combining system dynamic model and CLUE-S model to improve land use scenario analyses at regional scale: A case study of Sangong watershed in Xinjiang, China. Ecol. Complex. 7: 198–207.

Luo, Y., J. Arnold, P. Allen and X. Chen. 2012. Baseflow simulation using SWAT model in an inland river basin in Tianshan Mountains, Northwest China. Hydrol. Earth Syst. Sci. 16: 1259–1267.

Ma, X., J. Xu, Y. Luo, S.P. Aggarwal and J. Li. 2009. Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. Hydrol. Process. 23: 1179–1191.

Ma, X., J. Xu and M. van Noordwijk. 2010. Sensitivity of streamflow from a Himalayan catchment to plausible changes in land cover and climate. Hydrol. Process. 24: 1379–1390.

Mainstone, C.P. and W. Parr. 2002. Phosphorus in rivers – ecology and management. Sci. Total Environ. 282-283: 25–47.

Mainstone, C.P., R.M. Dils and P.J.A. Withers. 2008. Controlling sediment and phosphorus transfer to receiving waters – A strategic management perspective for England and Wales. J. Hydrol. 350: 131–143.

McVicar, T.R., L. Li, T.G. van Niel, L. Zhang, R. Li, Q. Yang, X. Zhang, X. Mu, Z. Wen, W. Liu, Y. Zhao, Z. Liu and P. Gao. 2007. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. Forest Ecol. Manage. 251: 65–81.

Meng, Q.H., B.J. Fu and L.Z. Yang. 2001. Effects of land use on soil erosion and nutrient loss in the Three Gorges Reservoir Area, China. Soil Use Manage. 17: 288–291.

Migliaccio, K.W., and I. Chaubey. 2008. Spatial Distributions and Stochastic Parameter Influences on SWAT Flow and Sediment Predictions. J. Hydrol. Eng. 13(4): 258–269.

Ming, X., Q. Xu and J. Yuan. 2009. Analysis of multi-factors affecting sediment load in the Three Gorges Reservoir. Quatern. Int. 208: 76–84.

Ministry of Water Resources of China. 1997. Standard for Classification and Gradation of Soil Erosion Standards. Press of China, Beijing. In Chinese.

Mishra, A., S. Kar and V.P. Singh. 2007. Prioritizing Structural Management by Quantifying the Effect of Land Use and Land Cover on Watershed Runoff and Sediment Yield, Water Resour. Manage. 21: 1899–1913.

Monteith, J.L. 1965. Evaporation and the environment. In The state and movement of water in living organisms. 19th Symposia of the Society for Experimental Biology. Cambridge University Press, London, UK. p. 205–234.

Morgan, T.K.K.B., D.N. Sardelic and A.F. Waretini. 2012. The Three Gorges Project: How sustainable? J. Hydrol. 460-461: 1–12.

Moriasi, D.N., J.G. Arnold, M.W. van Liew, R.L. Bingner, R.D. Harmel and T.L. Veith. 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50(3): 885–900.

Mukundan, R., D.E. Radcliffe and L.M. Risse. 2010. Spatial resolution of soil data and channel erosion effects on SWAT model predictions of flow and sediment. J. Soil Water Conserv. 65(2): 92–104.

Muleta, M.K. and J.W. Nicklow. 2005. Sensitivity and uncertainty analysis coupled with automatic calibration for a distributed watershed model. J. Hydrol. 306: 127–145.

Nakayama, T. and D. Shankman. 2013. Impact of the Three-Gorges Dam and water transfer project on Changjiang flats. Glob. Planet. Change 100: 38–50.

Nash, J.E. and J.V. Sutcliffe. 1970. River Flow Forecasting Through Conceptual Models. Part I: A Discussion of Principles. J. Hydrol., 10(3): 282–290.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry and J.R. Williams. 2005. Soil and Water Assessment Tool Theoretical Documentation Version 2005, Grassland, Soil and Water Research Laboratory and Blackland Research Center, Temple, TX.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan and J.R. Williams. 2010. Soil and Water Assessment Tool Input/Output File Documentation Version 2009, Grassland, Soil and Water Research Laboratory and Blackland Research Center, Temple, Texas Water Resources Institute Technical Report No. 365. College Station, TX.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry and J.R. Williams. 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009, Texas Water Resources Institute Technical Report No. 406. Texas A&M University System, College Station, TX.

Ng, S., Q. Cai, S. Ding, K. Chau and J. Qin. 2008. Effects of contour hedgerows on water and soil conservation, crop productivity and nutrient budget for slope farmland in the Three Gorges Region (TGR) of China. Agrofor. Syst. 74: 279–291.

NRCS Soil Survey Staff, 1996. National soil survey handbook, title 430-VI, U.S. Government Printing Office, Washington, D.C.

Olivera, F., M. Valenzuela, R. Srinivasan, J. Choi, H. Cho, S. Koka and A. Agrawal. 2006. ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT. JAWRA 42(2): 295–309.

Ongley, E.D., X. Zhang and T. Yu. 2010. Current status of agricultural and rural non-point source pollution assessment in China. Environ. Pollut. 158: 1159–1168.

Ouyang, W., F.-H. Hao, X. Wang and H.-G. Cheng. 2008. Nonpoint Source Pollution Responses Simulation for Conversion Cropland to Forest in Mountains by SWAT in China. Environ. Manage. 41: 79–89.

Ouyang, W., X. Wang, F. Hao and R. Srinivasan. 2009. Temporal-spatial dynamics of vegetation variation on non-point source nutrient pollution. Ecol. Model. 220: 2702–2713.

Ouyang, W., A.K. Skidmore, F. Hao and T. Wang. 2010. Soil erosion dynamics response to landscape pattern. Sci. Total Environ. 408: 1358–1366.

Panagopoulos, Y., C. Makropoulos, E. Baltas and M. Mimikou. 2011. SWAT parameterization for the identification of critical diffuse pollution source areas under data limitations. Ecol. Model. 222: 3500–3512.

Parajuli, P.B., N.O. Nelson, L.D. Frees and K.R. Mankin. 2009. Comparison of AnnAGNPS and SWAT model simulation results in USDA-CEAP agricultural watersheds in south-central Kansas. Hydrol. Process. 23, 748–763.

Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100: 81–92.

Qi, C. and S. Grunwald. 2005. GIS-Based Hydrologic Modeling in the Sandusky Watershed Using SWAT. Trans. ASAE 48(1): 169–180.

Qiu, L.J., F.L. Zheng and R.S. Yin. 2012. SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges. Int. J. Sediment Res. 27: 226–234.

Rathjens, H. and N. Oppelt. 2012. SWATgrid: An interface for setting up SWAT in a grid-based discretization scheme. Comput. Geosci. 45: 161–167.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool and D.C. Yoder. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture, Agriculture Handbook No. 703: 404 pp.

Rocha, E.O., M.L. Calijuri, A.F. Santiago, L.C. de Assis and L.G.S. Alves. 2012. The Contribution of Conservation Practices in Reducing Runoff, Soil Loss, and Transport of Nutrients at the Watershed Level. Water Resour. Manage. 26: 3831–3852.

Romanowicz, A.A., M. Vanclooster, M. Rounsevell and I. La Junesse. 2005. Sensitivity of the SWAT model to the soil and land use data parametrisation: a case study in the Thyle catchment, Belgium. Ecol. Model. 187: 27–39.

Rosgen, D.L. 1994. A classification of natural rivers. Catena 22: 169–199.

RWCSCB (Rural Water Conservancy and Soil Conservation Bureau, Changjiang River Water Resources Commission). 1998. Technologic Manual of Soil and Water Conservation of Changjiang Basin. Standards Press of China, Beijing. In Chinese.

Saghafian, B., S. Sima, S. Sadeghi and F. Jeirani. 2012. Application of unit response approach for spatial prioritization of runoff and sediment sources. Agric. Water Manage. 109: 36–45.

Sahin, V. and M.J. Hall. 1996. The effects of afforestation and deforestation on water yields. J. Hydrol. 178: 293–309.

Santhi, C., R. Srinivasan, J.G. Arnold and J.R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environ. Modell. Softw. 21: 1141–1157.

Scheffer, F., P. Schachtschabel, H.-P. Blume, G. Brümmer K.-H. Hartge, U. Schwertmann, W.R. Fischer, M. Renger and O. Strebel. 1992. Lehrbuch der Bodenkunde. Enke, Stuttgart. In German.

Schönbrodt, S., P. Saumer, T. Behrens, C. Seeber and T. Scholten. 2010. Assessing the USLE Crop and Management Factor C for Soil Erosion Modeling in a Large Mountainous Watershed in Central China. J. Earth Sci. 21(6): 835–845.

Schönbrodt, S., D. Ehret, C. Seeber, T. Behrens, M. Frei, J. Rohn, L. King, H. Kaufmann, W. Xiang, G. Subklew and T. Scholten. 2011. Geo-risks in the Highly Dynamic Three Gorges Reservoir Ecosystem: Interactions of Soil Erosion, Mass Movements, and Land Use. Earth Surf. Processes Landforms. Submitted.

Schönbrodt-Stitt, S., T. Behrens, X. Shi and T. Scholten. 2012. GIS-basierte Erfassung und Analyse der Bodenerosion durch Wasser im Drei-Schluchten-Ökosystem. In: Scholten T., Schönbrodt-Stitt S. (Eds.): Umweltforschung im Drei-Schluchten-Ökosystem in China – Ergebnisse der Forschungsarbeiten zur Risikoabschätzung von Bodenerosion, Hangrutschungen, diffusen Stoffeinträgen und Landnutzungswandel. Tübinger Geographische Studien Heft 151, Tübingen, pp 27–83. In German.

Scholten, T. and S. Schönbrodt-Stitt (Eds.). 2012. Umweltforschung im Drei-Schluchten-Ökosystem in China – Ergebnisse der Forschungsarbeiten zur Risikoabschätzung von Bodenerosion, Hangrutschungen, diffusen Stoffeinträgen und Landnutzungswandel. Tübinger Geographische Studien Heft 151, Tübingen. In German.

Schuol, J. and K.C. Abbaspour. 2006. Calibration and uncertainty issues of a hydrological model (SWAT) applied to West Africa, Adv. Geosci. 9: 137–143.

SCS (Soil Conservation Service). 1972. Section 4: Hydrology, in: National Engineering Handbook, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C.

Seeber, C., H. Hartmann, W. Xiang and L. King. 2010. Land Use Change and Causes in the Xiangxi Catchment, Three Gorges Area Derived from Multispectral Data. J. Earth Sci. 21(6): 846–855.

Seeber, C., M. Wiegand, W. Xiang and L. King. 2012. Landnutzungsklassifizierung und Analyse der Vulnerabilität von Risikoelementen bei Massenbewegungen im Einzugsgebiet des Xiangxi. In: Scholten T., Schönbrodt-Stitt S. (Eds.): Umweltforschung im Drei-Schluchten-Ökosystem in China – Ergebnisse der Forschungsarbeiten zur Risikoabschätzung von Bodenerosion, Hangrutschungen, diffusen Stoffeinträgen und Landnutzungswandel. Tübinger Geographische Studien Heft 151, Tübingen, pp 84–141. In German.

Shankman, D., L. Davis and J. de Leeuw. 2009. River management, landuse change, and future flood risk in China’s Poyang Lake region. Intl. J. River Basin Manage. 7(4): 423–431.

Shen, Z., Q. Hong, H. Yu and R. Liu. 2008. Parameter uncertainty analysis of the non-point source pollution in the Daning River watershed of the Three Gorges Reservoir Region, China. Sci. Total Environ. 405: 195–205.

Shen, Z.Y., Y.W. Gong, Y.H. Li, Q. Hong, L. Xu and R.M. Liu. 2009. A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agric. Water Manage. 96: 1435–1442.

Shen, Z., Q. Hong, H. Yu and J. Niu. 2010a. Parameter uncertainty analysis of non-point source pollution from different land use types. Sci. Total Environ. 408: 1971–1978.

Shen, Z., Y. Gong, Y. Li and R. Liu. 2010b. Analysis and modeling of soil conservation measures in the Three Gorges Reservoir Area in China. Catena 81: 104–112.

Shen, Z., Q. Liao, Q. Hong and Y. Gong. 2011. An overview of research on agricultural non-point source pollution modeling in China. Separation and Purification Technology. In press. doi: 10.1016/j.seppur.2011.01.018.

Shen, Z., L. Chen, Q. Liao, R. Liu and Q. Hong. 2012. Impact of spatial rainfall variability on hydrology and nonpoint source pollution modeling. J. Hydrol. 472-473: 205–215.

Shi, D.M., Y.S. Yang and X.X. Lu. 1992. Analysis of soil erosion characteristics and sediment sources for the Yangtze Three Gorges region. Int. J. Sediment Res. 7(2): 1–22.

Shi, P., C. Chen, R. Srinivasan, X. Zhang, T. Cai, X. Fang, S. Qu, X. Chen and Q. Li. 2011. Evaluating the SWAT Model for Hydrological Modeling in the Xixian Watershed and a Comparison with the XAJ Model. Water Resour. Manage. 25: 2595–2612.

Shi, Z.H., C.F. Cai, S.W. Ding, T.W. Wang, and T.L. Chow. 2004. Soil conservation planning at the small watershed level using RUSLE with GIS: a case study in the Three Gorge Area of China. Catena 55: 33–48.

Shi, Z.H., L.D. Chen, N.F. Fang, D.F. Qin and C.F. Cai. 2009. Research on the SCS-CN initial abstraction ratio using rainfall-runoff event analysis in the Three Gorges Area, China. Catena 77: 1–7.

Shi, X.Z., D.S. Yu, S.X. Xu, E.D. Warner, H.J. Wang, W.X. Sun, Y.C. Zhao and Z.T. Gong. 2010. Cross-reference for relating Genetic Soil Classification of China with WRB at different scales. Geoderma 155: 344–350.

Sivapalan, M., K. Takeuchi, S.W. Franks, V.K. Gupta, H. Karambiri, V. Lakshmi, X. Liang, J.J. McDonnell, E.M. Mendiondo, P.E. O'Connell, T. Oki, J.W. Pomeroy, D. Schertzer, S. Uhlenbrook and E. Zehe. 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an exciting future for the hydrological sciences, Hydrol. Sci. J. 48(6): 857–880.

Song, L. and J. Zhang. 2012. Hydrological Response to Climate Change in Beijiang River Basin Based on the SWAT Model. Proc. Eng. 28: 241–245.

Subklew, G., J. Ulrich, L. Fürst and A. Höltkemeier. 2010. Environmental Impacts of the Yangtze Three Gorges Project: An Overview of the Chinese-German Research Cooperation, J. Earth Sci., 21(6): 817–823.

Subklew, G., W. Xiang, S. Schönbrodt-Stitt and T. Scholten. 2012. Der Drei-Schluchten Staudamm am Yangtze und seine ökologischen Implikationen - eine Einführung. In: Scholten T., Schönbrodt-Stitt S. (Eds.): Umweltforschung im Drei-Schluchten-Ökosystem in China – Ergebnisse der Forschungsarbeiten zur Risikoabschätzung von Bodenerosion, Hangrutschungen, diffusen Stoffeinträgen und Landnutzungswandel. Tübinger Geographische Studien Heft 151, Tübingen, pp 1–10. In German.

Tan, Y. and F. Yao. 2006. Three Gorges Project: Effects of Resettlement on the Environment in the Reservoir Area and Countermeasures. Popul. Environ. 27: 351–371.

Tang, F.F., H.S. Xu and Z.X. Xu. 2012. Model calibration and uncertainty analysis for runoff in the Chao River Basin using sequential uncertainty fitting. Proc. Environ. Sci. 13: 1760–1770.

Tian, Y., Z. Huang and W. Xiao. 2010. Reductions in non-point source pollution through different management practices for an agricultural watershed in the Three Gorges Reservoir Area. J. Environ. Sci. (Beijing, China) 22(2): 184–191.

Tong, S.T.Y. and W. Chen. 2002. Modeling the relationship between land use and surface water quality. J. Environ. Manage. 66: 377–393.

Tripathi, M.P., R.K. Panda and N.S. Raghuwanshi. 2003. Identification and Prioritisation of Critical Sub-watersheds for Soil Conservation Management using the SWAT Model. Biosyst. Eng. 85(3): 365–379.

Tullos, D. 2009. Assessing the influence of environmental impact assessments on science and policy: An analysis of the Three Gorges Project. J. Environ. Manage. 90: S208–S223.

Ullrich, A. and M. Volk, 2009. Application of the Soil and Water Assessment Tool (SWAT) to predict the impact of alternative management practices on water quality and quantity. Agric. Water Manage. 96: 1207–1217.

USDA Soil Conservation Service. 1972. National Engineering Handbook, Section 4, Hydrology. U.S. Gov. Print. Office, Washington, DC.

Vaché, K.B., J.M. Eilers and M.V. Santelmann. 2002. Water Quality Modeling of Alternative Agricultural Scenarios in the U.S. Corn Belt. JAWRA 38(3): 773–787.

Vandewiele, G.L., C.-Y. Xu and Ni-Lar-Win. 1992. Methodology and comparative study of monthly water balance models in Belgium, China and Burma. J. Hydrol. 134: 315–347.

Van Griensven, A. and T. Meixner. 2007. A global and efficient multi-objective auto-calibration and uncertainty estimation method for water quality catchment models. J. Hydroinform. 09.4: 277–291.

Van Rompaey, A.J.J., G. Govers, E. van Hecke and K. Jacobs. 2001. The impacts of land use policy on the soil erosion risk: a case study in central Belgium. Agric. Ecosyst. Environ. 83: 83–94.

Verburg, P.H. and A. Veldkamp. 2001. The role of spatially explicit models in land-use change research: a case study for cropping patterns in China. Agric. Ecosyst. Environ. 85: 177–190.

Wang, C., H. Ouyang, V. Maclaren, Y. Yin, B. Shao, A. Boland and Y. Tian. 2007. Evaluation of the economic and environmental impact of converting cropland to forest: A case study in Dunhua county, China. J. Environ. Manage. 85: 746–756.

Wang, L., L. Tang, X. Wang and F. Chen. 2010. Effects of alley crop planting on soil and nutrient losses in the citrus orchards of the Three Gorges Region. Soil Tillage Res. 110: 243–250.

Wang, L., Q. Cai, M. Zhang, L. Tan and L. Kong. 2011a. Longitudinal patterns of phytoplankton distribution in a tributary bay under reservoir operation. Quatern. Int. 244(2): 280–288.

Wang, L., Q. Cai, Y. Xu, L. Kong, L. Tan and M. Zhang. 2011b. Weekly dynamics of phytoplankton functional groups under high water level fluctuations in a subtropical reservoir-bay. Aquat. Ecol. doi: 10.1007/s10452-010-9346-4.

Wang, S., S. Kang, L. Zhang and F. Li. 2008. Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. Hydrol. Process. 22: 2502–2510.

Wang, Y., Z. Shen, J. Niu and R. Liu. 2009. Adsorption of phosphorus on sediments from the Three-Gorges Reservoir (China) and the relation with sediment compositions. J. Hazard. Mater. 162: 92–98.

White, M.J., D.E. Storm, P.R. Busteed, S.H. Stoodley and S.J. Phillips. 2009. Evaluating Nonpoint Source Critical Source Area Contributions at the Watershed Scale. J. Environ. Qual. 38(4): 1654–1663.

Williams, J.R. 1969. Flood routing with variable travel time of variable storage coefficients, Trans. ASAE, 12(1): 100–103.

Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resour. Bull. 11(5): 965–974.

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook 282, USDA-ARS.

Wu, Y. and J. Chen. 2009. Simulation of nitrogen and phosphorus loads in the Dongjiang River basin in South China using SWAT. Frontiers of Earth Science in China 3: 273–278.

Xie, X. and Y. Cui. 2011. Development and test of SWAT for modeling hydrological processes in irrigation districts with paddy rice. J. Hydrol. 396: 61–71.

Xu, C.-Y. 2001. Statistical Analysis of Parameters and Residuals of a Conceptual Water Balance Model – Methodology and Case Study, Water Resour. Manage. 15: 75–92.

Xu, H., R.G. Taylor, D.G. Kingston, T. Jiang, J.R. Thompson and M.C. Todd. 2010a. Hydrological modeling of River Xiangxi using SWAT2005: A comparison of model parameterizations using station and gridded meteorological observations. Quatern. Int. 226: 54–59.

Xu, K. and J.D. Milliman. 2009. Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. Geomorphol. 104: 276–283.

Xu, X., Y. Tan, G. Yang and H. Li. 2011a. Three Gorges Project: effects of resettlement on nutrient balance of the agroecosystems in the reservoir area. J. Environ. Plan. Manage. 54(4): 517–537.

Xu, Y., Q. Cai, X. Han, M. Shao and R. Liu. 2010b. Factors regulating trophic status in a large subtropical reservoir, China. Environ. Monit. Assess. 169: 237–248.

Xu, Y., M. Zhang, L. Wang, L. Kong and Q. Cai. 2011b. Changes in water types under the regulated mode of water level in Three Gorges Reservoir, China. Quatern. Int. In press. doi: 10.1016/j.quaint.2011.01.019.

Xu, Z., J. Xu, X. Deng, J. Huang, E. Uchida and S. Rozelle. 2006. Grain for Green versus Grain: Conflict between Food Security and Conservation Set-Aside in China. World Dev. 34: 130–148.

Xu, Z.X., J.P. Pang, C.M. Liu, and J.Y. Li. 2009. Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model. Hydrol. Process. 23: 3619–3630.

Yang, J., P. Reichert, K.C. Abbaspour and H. Yang. 2007. Hydrological modelling of the Chaohe Basin in China: Statistical model formulation and Bayesian inference. J. Hydrol. 340: 167–182.

Yang, J., P. Reichert, K.C. Abbaspour, J. Xia and H. Yang. 2008. Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. J. Hydrol. 358: 1–23.

Yang, Q., F.R. Meng, Z. Zhao, T.L. Chow, G. Benoy, H.W. Rees and C.P.-A. Bourque. 2009. Assessing the impacts of flow diversion terraces on stream water and sediment yields at a watershed level using SWAT model. Agric. Ecosyst. Environ. 132: 23–31.

Yang, S., G. Dong, D. Zheng, H. Xiao, Y. Gao and Y. Lang. 2011. Coupling Xinanjiang model and SWAT to simulate agricultural non-point source pollution in Songtao watershed of Hainan, China. Ecol. Model. 222: 3701–3717.

Ye, L., Y. Xu, X. Han and Q. Cai. 2006. Daily Dynamics of Nutrients and Chlorophyll a during a Spring Phytoplankton Bloom in Xiangxi Bay of the Three Gorges Reservoir. J. Freshw. Ecol. 21(2): 315–321.

Ye, L., X.Q. Han, Y.Y. Xu, and Q.H. Cai. 2007. Spatial analysis for spring bloom and nutrient limitation in Xiangxi bay of three Gorges Reservoir. Environ. Monit. Assess. 127: 135–145.

Ye, L., Q. Cai, R. Liu R and M. Cao. 2009. The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region. Environ. Geol. 58: 937–942.

Yin, R., Q. Xiang, J. Xu and X. Deng. 2010. Modeling the Driving Forces of the Land Use and Land Cover Changes Along the Upper Yangtze River of China. Environ. Manage. 45: 454–465.

Yu, G., B. Xue, G. Lai, F. Gui and X. Liu. 2007. A 200-year historical modeling of catchment nutrient changes in Taihu basin, China. Hydrobiologia 581: 79–87.

Zeng, H., L. Song, Z. Yu and H. Chen. 2006. Distribution of phytoplankton in the Three-Gorge Reservoir during rainy and dry seasons. Sci. Total Environ. 367: 999–1009.

Zhang, J., Z. Liu and X. Sun. 2009. Changing landscape in the Three Gorges Reservoir Area of Yangtze River from 1977 to 2005: Land use/land cover, vegetation cover changes estimated using multi-source satellite data. Int. J. Appl. Earth Obs. Geoinf. 11: 403–412.

Zhang, J.-L., B.-H. Zheng, L.-S. Liu, L.-P. Wang, M.-S. Huang and G.-Y. Wu. 2010a. Seasonal variation of phytoplankton in the DaNing River and its relationships with environmental factors after impounding of the Three Gorges Reservoir: A four-year study. Proc. Environ. Sci. 2: 1479–1490.

Zhang, Q.L., Y.X. Chen, G. Jilani, I.H. Shamsi and Q.G. Yu. 2010b. Model AVSWAT apropos of simulating non-point source pollution in Taihu lake basin. J. Hazard. Mater. 174: 824–830.

Zhang, X., F. Hao., H. Cheng and D. Li. 2003. Application of SWAT model in the upstream watershed of the Luohe River. Chinese Geogr. Sci. 13(4): 334–339.

Zhang, X., R. Srinivasan and D. Bosch. 2009. Calibration and uncertainty analysis of the SWAT model using Genetic algorithms and Bayesian Model Averaging. J. Hydrol. 374: 307–317.

Zhang, X., R. Srinivasan, J. Arnold, R.C. Izzauralde and D. Bosch. 2011a. Simultaneous calibration of surface flow and baseflow simulations: a revisit of the SWAT model calibration framework. Hydrol. Process. 25: 2313–2320.

Zhang, X.Y., G. Hörmann, J.F. Gao and N. Fohrer. 2011b. Structural uncertainty assessment in a discharge simulation model. Hydrol. Sci. J. 56(5): 854–869.

Zhang, X., G. Hörmann, N. Fohrer and J. Gao. 2012a. Parameter calibration and uncertainty estimation of a simple rainfall-runoff model in two case studies. J Hydroinform. doi:10.2166/hydro.2012.084.

Zhang, X., G. Hörmann, N. Fohrer and J. Gao. 2012b. Estimating the impacts and uncertainty of changing spatial input data resolutions on streamflow simulations in two basins. J. Hydroinform. doi:10.2166/hydro.2012.085.

Zhang, Y., J. Xia, T. Liang and Q. Shao. 2010c. Impact of Water Projects on River Flow Regimes and Water Quality in Huai River Basin. Water Resour. Manage. 24: 889–908.

Zhao, G.J., G. Hörmann, N. Fohrer, H.P. Li, J.F. Gao and K. Tian. 2011. Development and application of a nitrogen simulation model in a data scarce catchment in South China. Agr. Water Manage. 98: 619–631.

Zhao, R.J., Y. Zuang, L. Fang, X. Liu and Q. Zhang. 1980. The Xinanjiang Model. IAHS AISH Publ. 129: 351–356.

Zhao, J., Q. Luo, H. Deng and Y. Yan. 2008. Opportunities and challenges of sustainable agricultural development in China. Phil. Trans. R. Soc. B 363: 893–904.

Zheng, J., Y. Gong, T. Hu and X. Yu. 2011. Simulation of non-point source pollution under different defarming scenarios in Bai River Basin. Energ. Proc. 13: 4315–4325.

Zhong, C., Z. Xing, W. Zhao, D. Wang, C. Deng, Y. Li and M. Xing. 2005. Eutrophication investigation and assessment of the Daning River after water storage of the Three Gorges Reservoir. Chin. J. Geochem. 24(2): 149–154.

Zhou, G., X. Zhao, Y. Bi, Y. Liang, J. Hu, M. Yang, Y. Mei, K. Zhu, L. Zhang and Z. Hu. 2011. Phytoplankton variation and its relationship with the environment in Xiangxi Bay in spring after damming of the Three-Gorges, China. Environ. Monit. Assess. doi: 10.1007/s10661-010-1571-8.

Zhu, Z., H. Bai, H. Xu and T. Zhu. 2011. An inquiry into the potential of scenario analysis for dealing with uncertainty in strategic environmental assessment in China. Environ. Impact Assess. Rev. 31: 538–548.

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Xiangxi River in July 2010

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation, abgesehen von der Beratung durch meine Betreuer, selbständig verfasst habe und keine weiteren Quellen und Hilfsmittel als die hier angegebenen verwendet habe. Diese Arbeit hat weder ganz noch in Teilen bereits an anderer Stelle einer Prüfungskommission zur Erlangung des Doktorgrades vorgelegen. Ich erkläre, dass die vorliegende Arbeit gemäß der Grundsätze zur Sicherung guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft erstellt wurde.

Kiel, 08. Januar 2013

(Katrin Bieger)